

**INVESTIGATION OF POOR CEMENTING BEHIND
OIL WELL CASING ACROSS ARAB-C AND D
FORMATIONS IN UTHMANIYAH**

BY

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In

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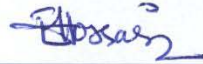
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This thesis, written by **ABDULLA FALEH AL-DOSSARY** under the direction of his thesis advisor and approval by his thesis committee, has been presented to and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN PETROLEUM ENGINEERING**

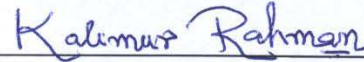
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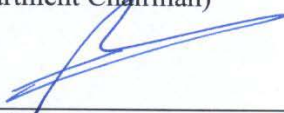
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**DIDICATED TO MY MOTHER'S
SOUL AND MY FATHER**

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خلاصة الرسالة

اسم الطالب كامل: عبدالله بن فالح الدوسري

عنوان الرسالة: أسباب رداءة الأسمنت بين طبقتي عرب-ج و د في أبار الزيت في حقل عثمانية النفطي

التخصص: هندسة بترول

تاريخ التخرج : يونيو 2011 م

هذه الرسالة تناقش الاسباب التي أدت الى رداءة الأسمنت بين طبقتي عرب-ج و د في أبار الزيت في حقل عثمانية النفطي . اساليب الحفر و تسميت الغلاف المعدني الموضوع بين هاتين الطبقتين روجعت و نوقشت بشكل علمي عن طريق مقارنتها بافضل الأساليب الأخرى المستخدمة في حقول أخرى . بالإضافة إلى ذلك، تم دراسة تأثير المياه الصخرية الموجودة في طبقة عرب-ج التي تحوي على غازات آكله للأسمنت من الناحية الميكانيكة و الكيميائية . أثناء الدراسة تم تعريض الأسمنت لمياه طبقة عرب-ج لمدتين زمنتين مختلفتين (ثلاثة و ستة أشهر) تحت ضغط مقداره 4000 رطل لكل قدم مكعب و درجة حراره مقداره 216 فهرنهايت. نتائج الدراسة و البحث بينت ان مياه طبقة عرب-ج ليس لها تأثير على الأسمنت بسبب قلة تركيز تلك الغازات التي تمثل 3 % فقط من تركيبة مياه طبقة عرب-ج. ايضا برهنت نتائج البحث ان السبب الرئيسي للمشكلة يعود الى عدم تمكن الأسمنت من تشكيل قوة تماسك كافية لمنع انتقال الماء الموجود في عرب-ج بسبب الضغط العالي الذي يزيح الأسمنت داخل الطبقات الصخرية ذات المسامية و النفاذية العالية فوق و تحت عرب-ج. إن السبب وراء هذه الظاهرة هو استخدام السدادة اعلى الغلاف المعدني الذي ادى الى انعزال الضغط الهيدروليكي للسائل فوق الاسمنت . في ضوء ذلك تم طرح بعض الحلول لهذه المشكلة

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Thesis Abstract

Full Name of Student: Abdullah Faleh Al-Dossary

Title of Study: INVESTIGATION OF POOR CEMENTING BEHIND OIL WELL CASING BETWEEN ARAB-C AND D FORMATIONS IN UTHMANYIA

Major Field: Petroleum Engineering

Date of Degree: June 2011

In Uthmaniyah field in Saudi Arabia, there is a persistent problem related to cementing at high pressure zones. Recently, communication between Arab-C (abnormally over pressurized zone) and D (low pressure zone) formations has occurred due to long term water injection with increasing frequency. As a result, production has been interrupted in several oil producers. This thesis addresses the problems through investigating field practices including drilling, cementing, and completion. It also reviews the field reports and cased hole logs. A three-month and six-month studies were conducted separately to evaluate the effects of Arab-C water on cement, where the cement was exposed to Arab-C water at simulated down hole conditions. The tests for permeability, mechanical properties TGA and EDXRF are presented. In addition, it highlights the final findings and presents recommendations as well.

MASTER OF SCIENCE DEGREE

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS

Dhahran-Saudi Arabia

Date: June 2011

Chapter 1

1.1 Introduction:

Gas migration in the annulus behind the casing has been recognized as one of the major completion problems in the drilling operations of oil and gas wells. Despite the efforts of many companies and individual researchers, the problem has remained unsolved. Gas migration in cement occurs during and after the cement is set. The main cause of gas channeling is early cement set at the permeable formation zones, which result in less hydrostatic head on the formation. Hence, due to high gas pressure, the gas will flow through the mud cake film and/or create micro-fractures through the fluid column of cement. Some of the factors which affect this phenomenon include: type of cement and their composition, additives, relationship of mud and cement density, temperature, pressure, mud cake film, mud and centralization, movement of casing string and reciprocation while pumping slurry, and cement filtrate.

Several theories have been proposed regarding gas migration during cement setting and hardening. These theories attribute the gas migration to (i) the fluid loss during cementing, and (ii) the differential pressure occurrence due to the gelation which precedes the cement setting. This differential pressure causes gas to migrate into the pores of the cement gel structure. A wide range of concepts pertaining to the solution of the problem of gas migration has been proposed. Theories which concentrate on one property of the cement or

mud while neglecting the change in other properties often create more difficulties than solving gas migration. These theories depend on the assumption that changes occurring in

some of the physical or chemical cement properties may be directly responsible for the gas migration.

However, changes occurring in the rest of the slurry properties were not considered. Micro-annulus is attributed to the cement inability to form a good bond with the casing. Micro-fractures are formed between cement and formation and within cement itself. Casing centralization, use of scratcher to clean mud cakes, and use of fluid spacers were some of the early ideas employed to solve the gas channeling problem, however, the application of these methods helped reduce gas channeling but could not eliminate it.

The two main reasons for gas channeling through a cemented annulus are (i) the mud cake that remains between cement and the permeable formations provides a weak zone for the passage of the water and gas, resulting to failures in cement jobs, and (ii) the inability of cement to hold the high fluid pressure at the period of its initial set which may cause water accumulation, resulting to micro-fracture within the cement body.

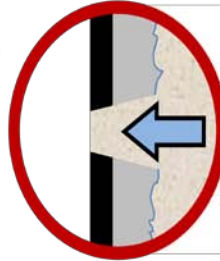
Lately, a water channeling has taken place in one of onshore fields here in KSA due to poor cementing. Poor cementing is ascribed to large difference in pressure between formations cemented. The communication problem has damaged the integrity of several wells which resulted in loss of oil production. This thesis unveils the reasons stand behind this problem and gives

1.2 Problem Statement

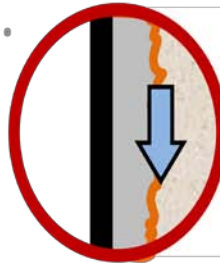
Arab-C/D zones communication problem emerged recently in several newly drilled and sidetracked wells in Uthmaniyah field. Three wells have reoccurrence of Arab-C casing leak. This problem is of a major concern that needs a quick intervention before it escalates and becomes a major issue. It is worth mentioning that Arab-C pressure in this area is higher than that of Arab-D for three main reasons. First of all, there is poor cement behind the casing across both zones. In addition, there is a leak in the cap rock between zones C and D through which massive quantities of injected water entered and overcharged Arab-C accidentally. Besides, pressure of Arab-D has dropped due to long time production. These factors together helped Arab-C pressure build up and become higher than the pressure of Arab-D zone.

The reason why it occurred has not been identified as yet. However, there are three possible explanations for this communication development. First, Arab-C made its own way behind the cement through mud cake and then entered the well as Arab-C pressure is higher than the pressure of the productive zone across Arab-D reservoir. Secondly, Arab-C gas transferred through cement channels and reacted with casing. As a result, the casing got corroded and hence holes developed, paving the road for Arab-C water to enter the wells and eventually killed them. Thirdly, water influx attacked cement and created a severe contamination in case the cement hydrostatic pressure was not enough to overbalance Arab-C high pressure allowing communication to take place while waiting on cement to set (WOC).

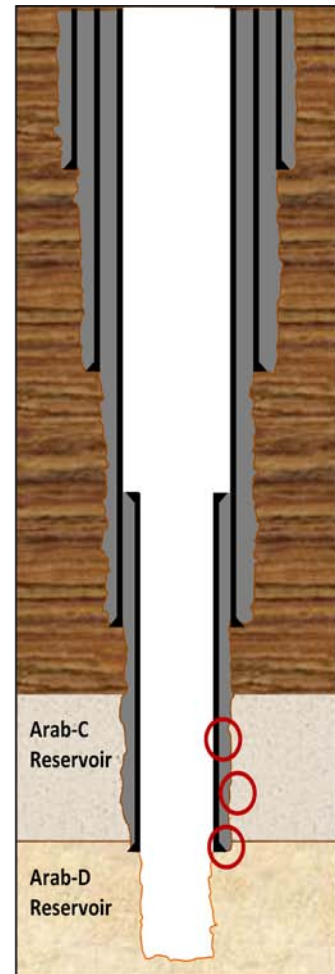
- Corrosion in 7" liner.



- Weak Zonal Isolation.



- Cement channeling.



Figure#1: Different scenarios of Communication occurrence

1.3 Objectives

1. Review the current cement practices at field and identify the main cause of cement failure.
2. Investigate experimentally the actual mix of cement slurry and design cement mix to solve the cement failure.

1.4 Approach

To achieve the above objectives, the following phases have been conducted:

Phase I

Review the current practices and identify the reasons behind the problem through reviewing and studying field data including:

- Completion Reports.
- Cased hole logs.
- Field practices.
- Experimentally investigate the effect of Arab-C water on cement.

Phase II

After identifying the causes, a solution will be suggested accordingly. The solution might be one of or all the followings;

- Cement system redesign
- Practices modification

Chapter 2

Literature review:

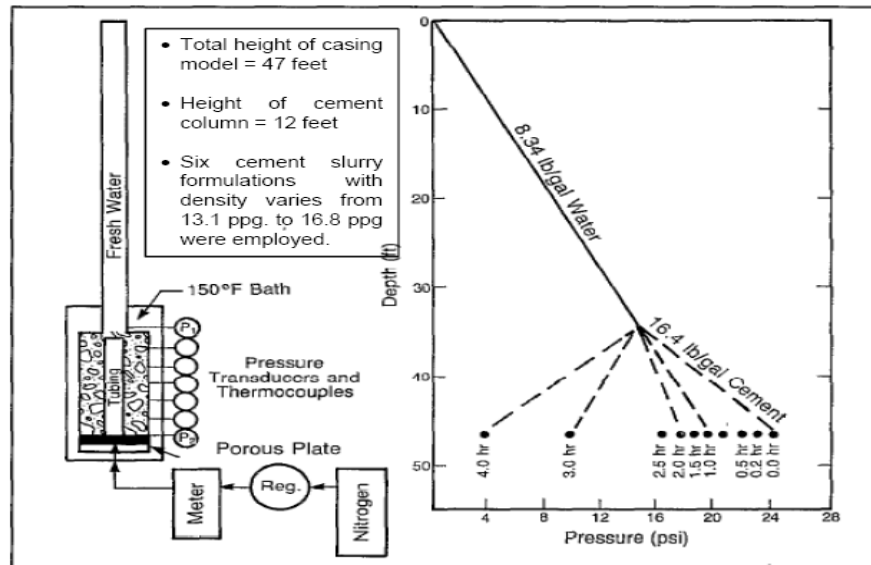
According to literature, there are several reasons that could cause communication problems behind the oil well casing in Uthmaniyah field. In order to narrow down the areas of investigations, we have searched the reasons that cause the same problem in areas elsewhere where similar practices have been implemented under the same circumstances. Accordingly, there are three scenarios that explained what happened exactly in this field as stated previously. Then, we further reviewed the literature in order to identify the root cause of the problem. This step has enabled us to pinpoint which one of them is the dominant factor that caused the problem.

Levine, Thomas and Bezner⁽¹⁾ (1978): They conducted an experiment to test the transmissibility of cement to pressure right after cement placement using different slurries and variable pressure above. The experiment apparatus as well as procedure are explained in detail. They observed that the cement is able to transfer pressure until it gets initial set when gel strength forms an effective seals which in turns makes the cement hydrostatic pressure drop. Moreover, the effect of density of mix water is significant on the cement ability to transfer pressure such that it increases the gradient of hydrostatic during thickening time or on other word the gelation process. However, the amount of mix water pressure will not make up for hydrostatic pressure as cement hydrates. They concluded at the end that the flow communication between lower and higher pressure formations will occur during dehydration time at the minute that hydrostatic pressure is less than that of formation. Therefore, the authors suggested a couple of measures to get

through this problem. One of these techniques is increasing mix water density by NaCl_2 in order to increase the hydrostatic pressure of the cement column. The other technique is to modify the cement slurry so that it maintains a fluid pressure gradient near the original density during gelation period. The research in this thesis focuses on this point in order to understand its impact on the integrity of the well.

Levine et al demonstrated that

- Loss of hydrostatic pressure in cement column occurred immediately after cement placement.
- Hydrostatic gradient of the cement column initially decreased slowly to cement water gradient
- When slurries attained their initial set, the hydrostatic pressure decreased rapidly to below the cement fluid water gradient
- The decrease to below the cement fluid gradient is believed as a result of shrinkage within the cement matrix due to cement hydration process and fluid loss incurred.
- Pressure can be transmitted through the static cement column until such time as the cement obtains its initial set.



Figure#2 Experimental set up to test cement transmissibility.⁽¹⁾

Cooke, Kluck and Medrano⁽²⁾ (1983): They studied and monitored the pressure behavior during and after pumping cement in three different wells by installing six pressure sensors on the casing at regular intervals which are connected all together with a logging cable to the surface. The equipment setup and procedure to get pressure readings are well explained in the technical paper. In the first well, after 30 minutes from pumping cement, 100 psi pressure was applied from the surface to see whether the cement hydrostatic will increase or not. None of the sensors detected the pressure indicating that cement has already developed enough gel strength that prevented cement from

transmitting pressure. No gas migration was observed as cement developed enough gel strength before hydrostatic pressure fell down blow formation pressure.

In the second well, 60 psi pressure was applied and seen by all sensors except the bottom most one indicating that gel strength between the last two sensors is higher than that above. Also, the pressure was not detected between 29 and 31 hours after pumping in the upper sensors showing that gel strength increased higher in that well. In addition, after 35 hrs the pressure was increased to 570 psi and as a result of that the pressure increased at all sensors and one hour later pressure at surface dropped all of a sudden. On other words, the pressure increased more rapidly and higher pressure could be applied before it decreased suddenly.

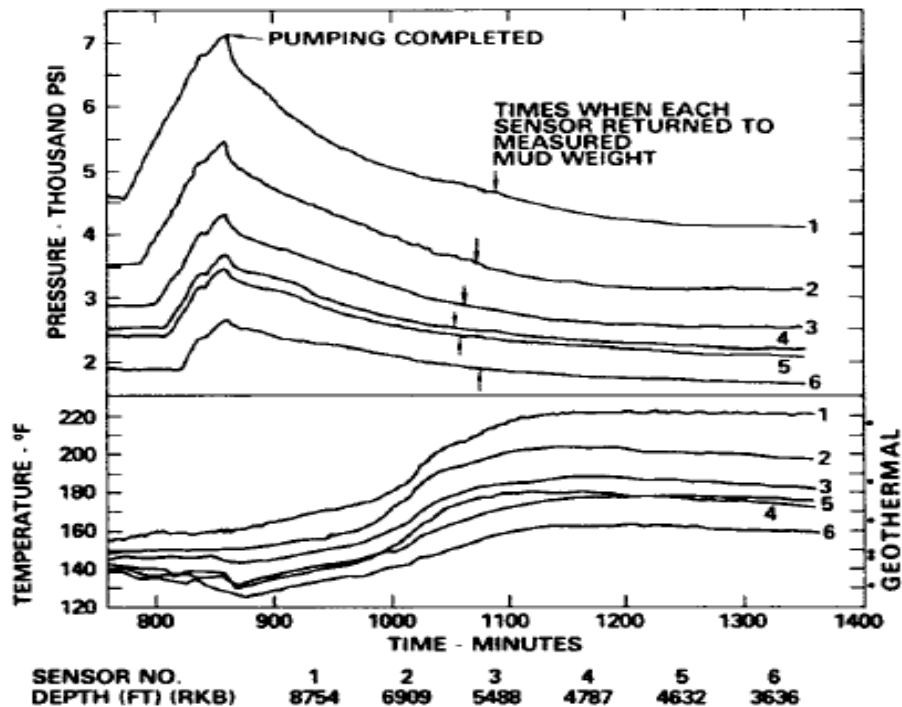
This high pressure is due to the fact that the gel strength was increasing up the well and cement column was resistant to flow. Also, the surface pressure did not increase until column was moved which is indicated by sudden decrease in surface pressure.

In the third well, the team observed that the pressure decreased at the lower sensor to pressure less than that of gas zone before cement had set allowing for gas flow to occur. After some time, pressure at the sensor increased to that of gas zone. The results of pressure and temperature readings taken in the cement column of these wells (Well-A, Well-B and Well-D) are shown below:

- **Successful Primary Cementing Job (well-A)**

Loss of hydrostatic pressure in cement column occurred immediately after the pumping was stopped. As can be seen in the plot shown (Fig#3), the pressure in the cement column in this well reduced to the mud weight gradient at about three hours after pumping was stopped.

Thereafter, the pressure in the cement column continued to decline. In their conclusion, Cooke et al mentioned that the pressure decline can be explained in terms of volume reduction of the cement accompanied by sufficient gel strength of the cement which prevented downward movement of the column.



Figure#3: Pressure and temperature Vs time for Well-A. ⁽²⁾

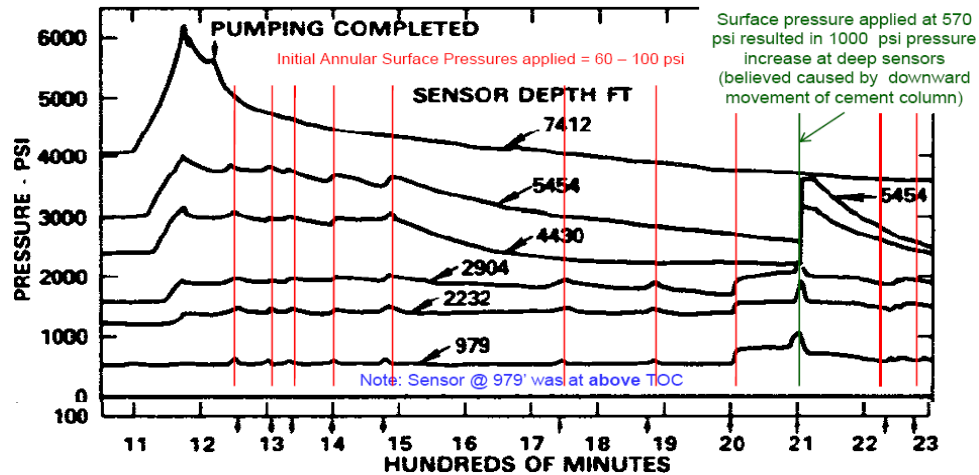
The surface pressure of 100 psi applied in the annulus at 24 minutes after pumping was stopped in this well and was not detected even by the top most sensor which was at about 2400' below top of cement. However, in Well B, the pressure was successfully transmitted down the cement column even after 15 hours and pumping was stopped when higher annular pressure (570 psi) was applied as shown in Fig#4.

In their conclusion, Cooke et al mentioned that:

- The effectiveness of applied surface pressure to prevent the pressure decline in cement column depends on the rate of cement gel strength development.
- Surface pressure can compensate for the volume reduction provided that the surface pressure applied is sufficient to break the cement gel strength. Whether this is possible depends on pressure limitations in the well and the degree of gel strength development in the cement.

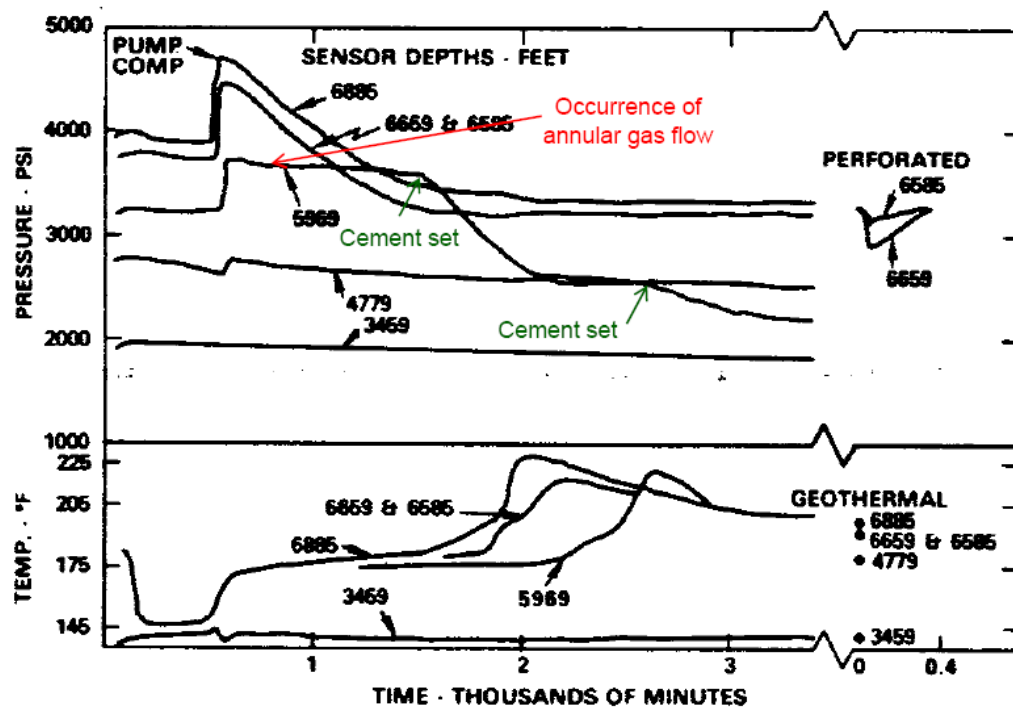
Also, they showed that the success of the primary cement job in Well 'A' in preventing annular fluid flow was due to the fact that the cement had began to set before pressures in the cement fell to below the pore pressures.

- Investigation on Application of Annular Surface Pressure



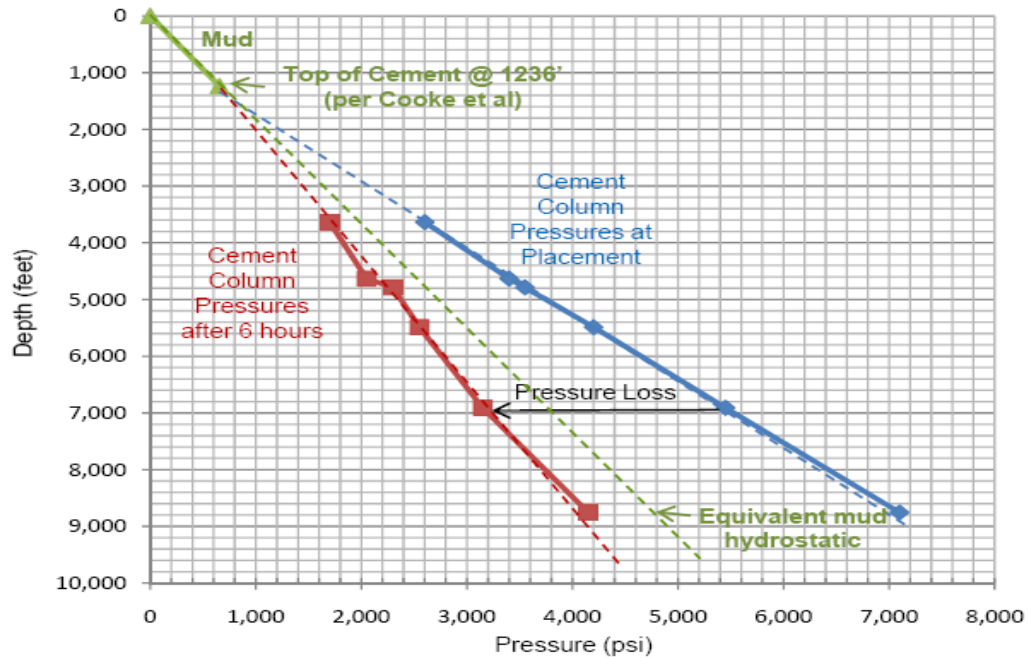
Figure#4: Effect of application of annular pressure.⁽²⁾

The surface pressures applied at 60 – 100 psi were initially detected by the shallow sensors as shown in Fig#4. At 2100 minutes, a 1000 psi increase in pressure was registered by the sensors at 4430' and 5454' when the surface pressure of 570 psi was applied. This shows that the cement gel strength can be overcome when sufficient annular pressure is applied.



Figure#5: Pressure and temperature versus time for Well-D.⁽²⁾

In their conclusion, Cooke et al mentioned that the formation fluid entered the wellbore when the cement column pressure dropped to formation cement pressure and the pressure in the wellbore stabilized at this value before the cement set as shown in Fig#5.



Figure#6: Pressure vs depth during the first six hours.⁽²⁾

Sensor Depth (feet)	Sensor Pressure (psi)		Pressure Loss (psi)
	At Cement Placement	6 hours after Placement	
3,636	2,600	1,700	900
4,632	3,400	2,050	1,350
4,787	3,550	2,300	1,250
5,488	4,200	2,550	1,620
6,909	5,450	3,150	2,300
8,754	7,100	4,150	2,950

Table#1: Pressure Vs depth during the first six hours following initial set.⁽²⁾

Farias, Suzart, Ribeiro, Santos and Santos⁽³⁾—(2007): Farias et.al observed a combination of factors must exist for gas migration to happen; Fluid loss, cement shrinkage, free water formation within cement, mechanical failure in cement sheath and dehydrated mud cake. They suggested that two factors should be present during the transition time- time during which cement transfers from liquid to solid state- in order to prevent fluid migration. The first is reduction of cement permeability and the second is increase in the growth rate of the static gel strength. They also suggested that the cement slurry designed for gas migration elimination should have little fluid loss, low viscosity, little water concentration, uniform thickening time and 500 lb/100 ft² gel strength in the first 15 mins of transition time. They mentioned that the existing filter cake cannot resist the gas flow due to restriction it causes since it gives up at 2 psi.

Hartog, Davies and Stewart⁽⁴⁾(1983): They recommended using shear thickening fluids that have increasing velocity with shear stress as it improves displacement efficiency specially in eccentric section where fluid normally flows up the wide annulus. In order to achieve such goal, highly thinned cement slurry is used. Also, they mentioned that the API HPHT (high pressure and high temperature) fluid loss should be at least of 200 cm³. They highlighted the importance of the contact time- time during which cement is in contact with hole wall- at all points since it improves mud cake removal. They recommended it to be four minutes where good isolation is required for better mud cake removal. In addition, the cement should be placed before it starts thickening to avoid damaging cement and decreasing cement displacement efficiency. They observed that

cement for 45 min using a batch mixer will increase the seven-hr compressive strength by 250 %.

Robert and Art⁽⁵⁾ (1973): The authors designed equipment that quantifies the effect of temperature, pressure and salts on expansion. During the tests they observed that with increased temperature and pressure the expansion decreases with little shrinkage at high levels of P and T to the contrary to salts with which cement expands more and more as their concentration within cement increases but with small amount of shrinkage at the beginning for salt quantity below 37.2%. The commercial expandable cement were also tested and found that they expand very high compared with cement contains salts.

Fred, John and David⁽⁶⁾ (1980): The team mentioned that gas flow occurs 30 minutes after cement placement while the communication between zones happens weeks after. They defined the transition time as the time during which cement changes from a truly hydraulic fluid to a highly viscous mass showing some solid properties. They also set a prediction method that calculates pore pressure of cement versus time. They found that the static gel strength develops and reaches 10 pa after 10 minutes from transition time start. Moreover, they stated that gel strength of 120 to 250 pa is enough to prevent gas flow.

Cheung and Robert⁽⁷⁾ (1985): They mentioned that although fluid loss control is beneficial, not enough to prevent gas flow. They stressed on the effect of mobility factor of fluid within cement after becomes load bearing. They recommended that it should be controlled in order to minimize gas flow. Moreover, authors set forth the gas migration mechanism in detail. In addition, they concluded from the experiments conducted that in order to prevent gas invasion, polymeric material and bridging agent should be used to form impermeable cement that immobilizes fluid within pore spaces. Additionally, they gave a comment that the gas bearing cement might not prevent gas invasion in case the generated gas bubbles coalesce and form channels accordingly.

Cheung and Myrick⁽⁸⁾ (1983): The authors highlighted the great role impermeable cement plays in gas flow prevention in different geological formation and various cement jobs. Based on the field results, the success ratio of such type of cement in preventing gas flow is as high as 90%. They also, mentioned that if cement is capable of immobilizing pore fluid within cement there is no need for fluid loss control and free water control additives.

Jones and Carpenter⁽⁹⁾ (1991): Introduced a new system that combines both latex and thexotropic cement systems. Lab tests as well as field findings showed that it prevents gas migration, provides high degree of zonal isolation, reduces filtrate loss and gives rapid compressive strength and minimal WOC.

A. Khodadadi,⁽²⁴⁾ (2008): He studied the root causes behind the gas migration problem in Khangiran wells. After an extensive literature review he made, he came to find that several factors could have contributed to gas migration in these wells. These factors are:

- Premature gelation
- Poor filter-cake removal
- Wrong cement density
- Excessive fluid loss
- Highly permeable slurry
- High cement shrinkage
- Cement failure under stress
- Poor interfacial bonding
- Poor mud removal
- Poor casing centralization
- Well parameters such as hole size, pipe and casing size, and total depth

Iverson et al,⁽²⁰⁾ (2008): They tested different cement types; neat cement, foamed cement and elastomer cement, to study their mechanical properties. In addition, they explained and discussed differences and contrasts in the results obtained (table#2).

	Neat	Foam	Elastomer
Modulus (psi)	1.81E+06	8.08E+05	4.91E+05
Comp. Strength (psi)	6851	1052	1350
Tens. Strength (psi)	429	190	218
Poisson's Ratio	0.2	0.151	0.205
Cohesion (psi)	2208	391	540
Friction Angle	24.84	12.49	13.58

Table#2: Mechanical properties for different cement mixes. After (Iverson et al).⁽³⁾

Backe et al.⁽²³⁾ (1999): They proposed a new mechanism for gas migration. They believe that after that gas has entered the pore system of cement, the gas inside will overcome the tensile strength of cement structure, break the cement matrix and travel through the micro fractures assuming that the hydrostatic pressure of cement column will decrease when that gas bubbles are already inside and gas will try to expand until that pressure difference is large enough to overcome cement tensile strength and in turn break cement. Also, they mentioned the important role that shrinkage factor plays after the initial set. They mentioned that lower that shrinkage rate the less the pressure decline of cement. In addition, they defined that total shrinkage is the summation of external and internal shrinkage. Moreover, they studied tensile strength, permeability and shrinkage of different cement recipes at 140 C. Based on the tensile strength build up, they defined a

time window, $\Delta t = t_2 - t_1$ that represents time when tensile strength is of 0.3 and 0.5 bars respectively.

The permeability is recorded at each time as well as pressure. These parameters were combined together in one equation to find a factor that can characterize the cement ability to resist gas migration. This factor is called; the gas tightness factor.

$$F_{gt} = \frac{\sqrt{\Delta t}(K_1 - K_2)}{K_1} K_2 \left(\frac{P_i - P_1}{P} + 1 \right)$$

According to the authors, threshold is somewhere between 5 and 20.

Larry et al.⁽¹⁹⁾ (2007): They conducted several tests to find out the differences in velocities and flow rates on the wide side and narrow side for nine different models with each of unique annulus geometries. The test procedures and equipment set up are explained and discussed in detail in the technical paper.

Moroni et al.⁽¹⁷⁾ (2009): They studied the effect of CO₂ on cement and presented solutions that enhance cement resistance to CO₂ and prolong its life. They reduced the permeability and shrinkage of cement. In addition, they changed the cement chemistry in order to reduce the materials emerging that react with CO₂ gas during the hydration process. Then, the enhanced cement was exposed to CO₂ gas at down hole conditions.

After that, cement sample was tested from chemistry and mechanics point of view. The findings showed that the newly designed system worked perfectly in CO₂ environment.

Ramirez et al.⁽¹⁸⁾ (2009): They presented new cement system with quick setting and enhanced mechanical properties to withstand operational changes. The designers focused on two physical properties of cement transition time and zero jel time as well. Cement samples were prepared and cured in for one week at simulated down hole conditions. After that, cement was tested for mechanical properties including tensile strength, Poisson's ratio and Young's modulus. The results of the study showed that this modified cement system can prevent water channeling and withstand high level of mechanical stresses.

Ashok et al.⁽¹⁹⁾ (2009): They studied the depth of carbonation for pozzollanic cement when is exposed to CO₂. Basically, they tested pozzollanic cement containing silica fume and fly ash of diverse compositions to quantify its resistance to carbonate after being exposed to CO₂ gas for weeks at high pressure and temperature. During the study, cement specimens were tested for TGA and XRF in order to find out the chemical change that occurred to the system. Both experimental work and findings were discussed and explained in detail in the paper.

Berg et al.⁽²²⁾ (2008): They improved the cement system used for HPHT and deep gas wells in KSA. This optimized cement system has very low permeability and porosity due

to the enhance particle packing. In addition, the rheological properties were improved to mitigate the settling problem encountered with high density cement.

Chapter 3

Review of Field Practices

Most of wells of Arab-C/D casing leak problem have been drilled to increase the oil production. These were drilled early 2006. Basically, these wells have been completed as either vertical or horizontal open hole Arab-D with 7" liner across Arab-C and D. All wells have been completed with 7" down hole packer and 4-1/2" tubing. Soon after first completion, these wells started producing Arab-C water and this was an indication of communication between Arab-C and D formations.

It is important to point out that the Arab-C formation has a pressure higher than that of Arab-D due to the poor cement behind the pipe, and leak in cap rock between Arab-D and Arab-C reservoirs. Large amounts of injection water entered Arab-C formation and over pressurized it as a result of this leak. In addition, Arab-D has lost some pressure due to long time production. Therefore, these factors all together helped Arab-C pressure build up and become higher than Arab-D pressure

In this chapter, a detailed review will be presented for field practices that were implemented in wells with communication problem. It will reveal drilling challenges such as drilling across Arab's formations, hole conditioning and cementing.

3.1 Well-A-1663 (Horizontal Open Hole Producer):

3.1.1 Drilling:

This well was drilled and completed as an Arab-D horizontal open hole producer in mid 2007. In this well, an 8-1/2" curve section (0-81 degrees) was drilled from two formations above Arab-A all the way down to 2' TVD above Arab-D zone-1 reservoir with full circulation. Mud weight was 64 pcf at start till Arab-C formation was hit when well started flowing at 40 BPH. The well then was shut in until pressure stabilized. The stabilized shut in pressure was 450 psi. The mud weight was increased to 84 pcf to kill Arab-C formation. After that, the rest of hole was drilled to Arab-D reservoir.

The hole was swept with viscous pills to effectively clean the well by improving cuttings lifting efficiency. In addition, a wiper trip was performed from the bottom up to 9-5/8" casing shoe to boost hole cleaning efficiency before running the 7" liner.

3.1.2 Running and Cementing 7" Production Liner:

7" liner was run consisting of Float Shoe, Float Collar, Landing Collar, 7" casing Joints and mechanical hanger along with Top Packer and tie back Receptacle. The casing was centralized as follows;

Every single joint till angle of 44 degrees and every second joint above to Kick-off point were centralized with a spiral centralizer, then every other joint was centralized with a collapsible centralizer to 9-5/8” casing Shoe and after that every third joint was centralized inside casing to 7” liner hanger using a bow rigid centralizer.

Upon reaching the bottom, the casing was rotated and reciprocated besides circulating the well at the highest possible rate in order to remove mud cake. Then, the mechanical liner hanger was set. After that, water spacer was pumped ahead of cement in order to remove any residual impurities and prevent any potential cement contamination if it gets in contact with mud. Then, the well was cemented using two-stage cement as follows;

Lead Cement

Class G + 0.6% (Dispersant) + 0.3% (Fluid loss) + 0.05gps (Retarder)+ 0.02 gps (Defoamer)	
Slurry weight	101 pcf
Thickening Time	5 – 5.5 hours
Slurry Yeild	1.08 cu ft/sack

Table#3: Lead cement recipe for well-A.

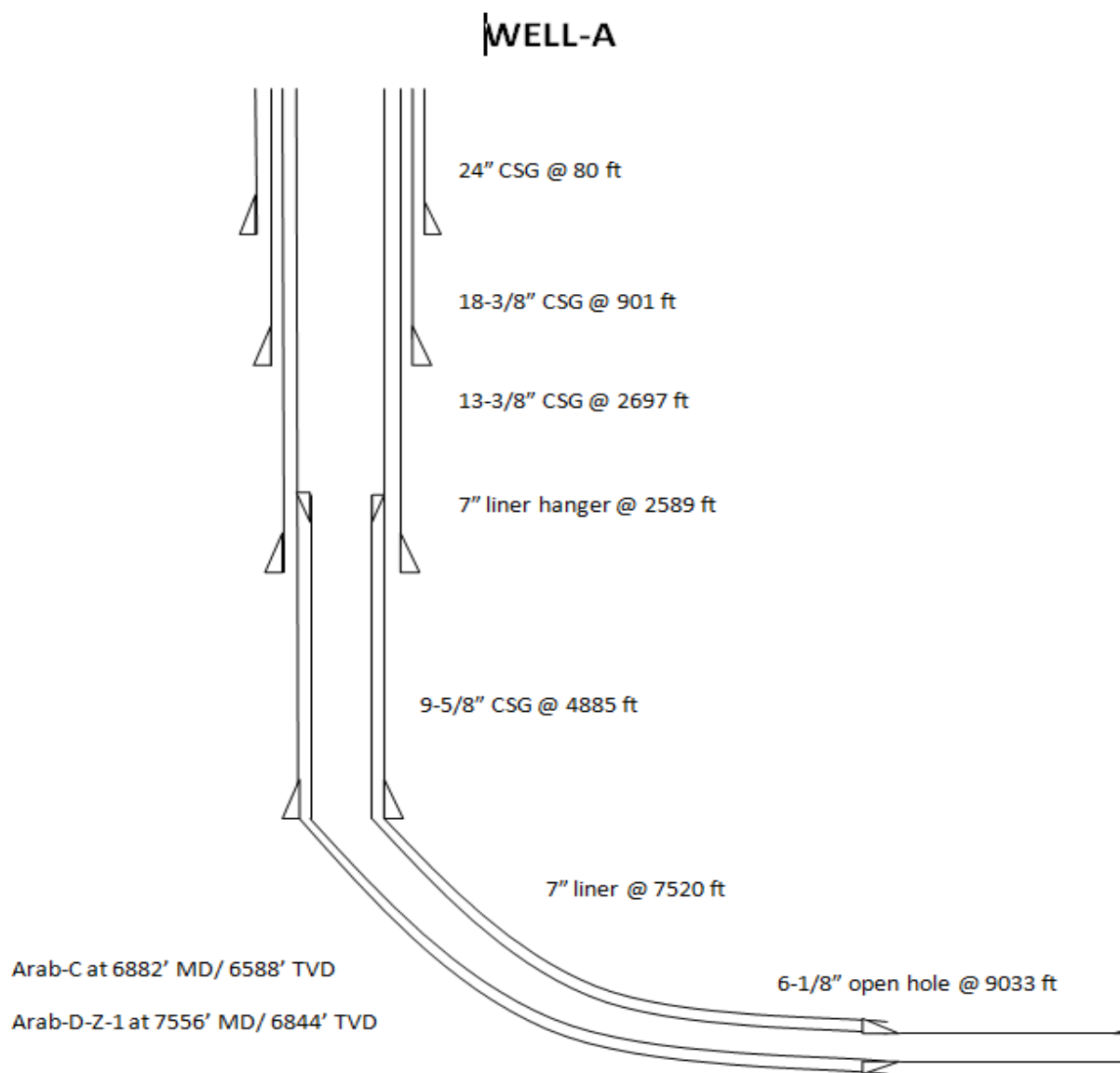
Tail Cement

Class G + 1.2% (Dispersant) + 0.4% (Fluid loss) + 0.22 % (Retarder)+ 0.01 gps (Defoamer)	
Slurry weight	122 pcf
Thickening Time	4– 5 hours
Slurry Yield	1.08 cu ft/sack

Table#4: Tail cement recipe for well-A.

At first, the lead cement (light cement) was pumped followed by the tail cement (heavy cement). Then, the dart was dropped and displaced by mud until it latched the wiper plug in the liner hanger. Then, the pressure was increased to shear the wiper plug and displaced until it landed in the landing collar. No lost circulation was encountered. At the end, the excess cement was reversed out before the liner top packer was set.

After WOC time had finished, a clean out trip was performed to drill out cement inside the liner plus float equipment. Then, the liner shoe was negative tested with water and no flow was observed. After that, the shoe was tested at 2000 psi with 71 pcf brine and the test was found good. The well was placed on production in late 2007 and it was producing oil with 0 % water cut for 5 months before became dead due to communication that was confirmed by water sampling and PLT log as well.



Figure#7: Well sketch for well-A

3.2 Well-B-1658 (Horizontal Open Hole Producer):

3.2.1 Drilling:

This well was drilled and completed as an Arab-D horizontal open hole producer in late 2007. In this well, an 8-1/2" curve section (0-80 degrees) was drilled from two formations above Arab-A all the way down to 2' TVD above Arab-D, zone-1 reservoir with full circulation. Mud weight was 64 pcf at start till Arab-C formation was hit when well started flowing at 25 BPH with H₂S traces. The mud weight was raised to 85 pcf to kill Arab-C formation. After that, the rest of hole was drilled to Arab-D reservoir. The hole was swept with viscous pill to effectively clean the well by improving cutting lifting efficiency. In addition, a wiper trip was performed from the bottom up to 9-5/8" casing shoe to boost hole cleaning efficiency before running the 7" liner.

3.2.2 Running and Cementing 7" production Liner:

7" liner was run consisting of Float Shoe, Float Collar, Landing Collar, 7" casing Joints and mechanical hanger along with Top Packer and tie back Receptacle. The casing was centralized as follows:

The first five joints and every second joint to 9-5/8" casing Shoe were centralized with a spiral centralizers and every third joint was centralized inside casing to 7" liner hanger using a bow rigid centralizer.

Upon reaching the bottom, the casing was rotated and reciprocated besides circulating the well at the highest possible rate in order remove mud cake. Then, the mechanical liner hanger was set. After that, water spacer was pumped ahead of cement in order to remove any residual impurities and prevent any potential cement contamination if it gets in contact with mud. Then, the well was cemented using two-stage cement as follows;

Lead Cement

Class G + 0.6% (Dispersant) + 0.3% (Fluid loss) + 0.05gps (Retarder)+ 0.02 gps (Defoamer)	
Slurry weight	101 pcf
Thickening Time	5 – 5.5 hours
Slurry Yeild	1.69 cu ft/sack

Table#5: Lead cement recipe for well-B.

Tail Cement

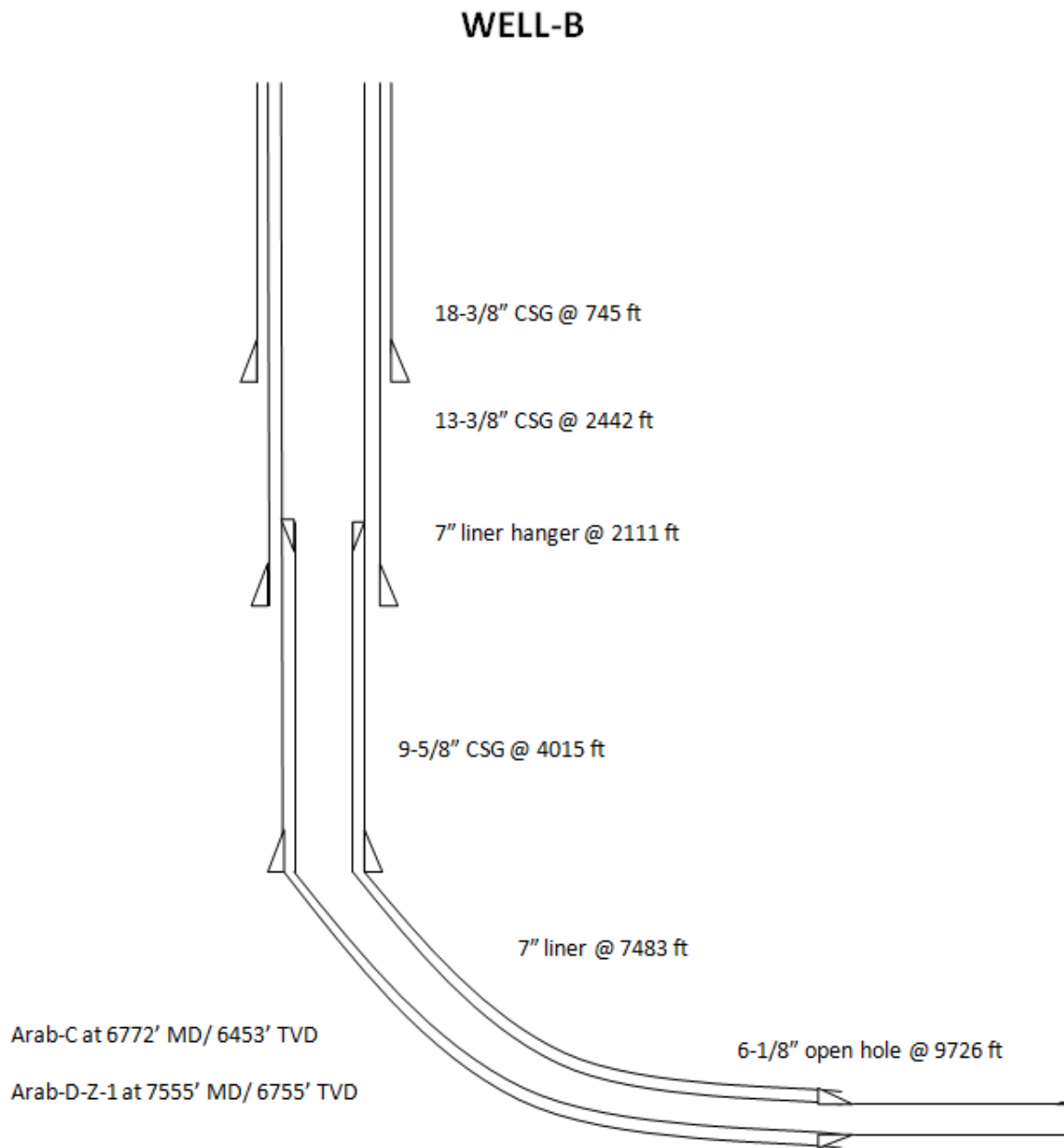
Class G + 1.2% (Dispersant) + 0.4% (Fluid loss) + 0.22 % (Retarder)+ 0.01 gps (Defoamer)	
Slurry weight	122 pcf
Thickening Time	4– 5 hours
Slurry Yeild	1.08 cu ft/sack

Table#6: Tail cement recipe for well-B.

At first, the lead cement (light cement) was pumped followed by the tail cement (heavy cement). Then, the dart was dropped and displaced by mud until it latched the wiper plug in the liner hanger. Then, the pressure was increased to shear the wiper plug and displaced until it landed in the landing collar. No lost circulation was encountered. At the end, the excess cement was reversed out before the liner top packer was set.

After WOC time had finished, a clean out trip was performed to drill out cement inside the liner plus float equipment till 10 ft above shoe before that liner was tested with water to 2000 psi. No leak was observed. After that, the shoe was drilled and a 10' ft rat hole. Then, the well flowed slightly before being killed with 64 pcf brine.

The well was placed on production in mid 2008 and it was producing oil with 2 % water cut for 6 months before became dead due to communication that was confirmed by water sampling and PLT log as well.



Figure#8: Well sketch for well-B

3.3 Well-C-1589 (Vertical Cased Hole Producer):

3.3.1 Drilling:

This well was drilled and completed as an Arab-D Vertical open hole producer in late 2005. In this well, an 8-1/2" open hole was drilled from two formations above Arab-A all the way down to 2' TVD above Arab-D, zone-1 reservoir with full circulation. Mud weight was 64 pcf at start till Arab-C formation was hit when well started flowing at 25 BPH with H₂S traces. The mud weight was raised to 87 pcf to kill Arab-C formation. After that, the rest of hole was drilled to Arab-D reservoir. The hole was swept with viscous pill to effectively clean the well by improving cutting lifting efficiency. In addition, a wiper trip was performed from the bottom up to 9-5/8" casing shoe to boost hole cleaning efficiency before running the 7" liner.

3.3.2 Running and cementing 7" production Liner:

7" liner was run consisting of Float Shoe, Float Collar, Landing Collar, 7" casing Joints and mechanical hanger along with Top Packer and tie back Receptacle. The liner was centralized as follows;

The first five joints and then every second joint to 9-5/8" casing shoe were centralized with collapsible Centralizers and every third joint was centralized inside casing to 7" liner hanger using a bow rigid centralizer.

Upon reaching the bottom, the casing was rotated and reciprocated besides circulating the well at the highest possible rate in order remove mud cake. Then, the liner hanger was set. After that, water spacer was pumped ahead of cement in order to remove any residual impurities and prevent any potential cement contamination if it gets in contact with mud. Then, the well was cemented using two-stage cement as follows;

Lead Cement

Class G + 0.7% (Dispersant) + 0.3% (Fluid loss) + 0.02 gps (Defoamer)	
Slurry weight	101 pcf
Thickening Time	4 hours
Slurry Yield	1.69 cu ft/sack

Table#7: Lead cement recipe for well-C.

Tail Cement

Class G + 0.65% (Dispersant) + 0.3% (Fluid loss) + 0.05 % (Retarder)+ 0.01 gps (Defoamer)	
Slurry weight	122 pcf
Thickening Time	4– 5 hours
Slurry Yield	1.08 cu ft/sack

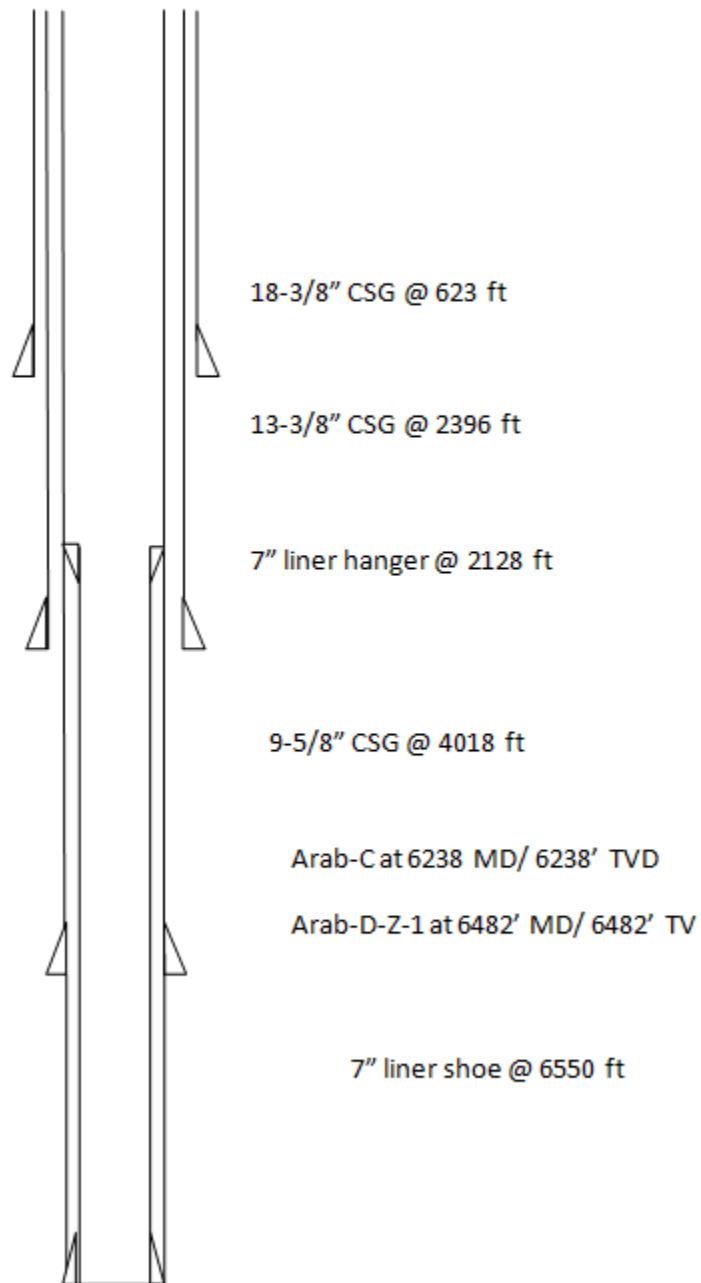
Table#8: Tail cement recipe for well-C.

At first, the lead cement (light cement) was pumped followed by the tail cement (heavy cement). Then, the dart was dropped and displaced by mud until it latched the wiper plug in the liner hanger. Then, the pressure was increased to shear the wiper plug and displaced until it landed in the landing collar. No lost circulation was encountered. At the end, the excess cement was reversed out before the liner top packer was set.

After WOC time had finished, a clean out trip was performed to drill out cement inside the liner, and also drill the float equipment till 10 ft above shoe, before that liner was tested with water to 2000 psi. No leak was observed. After that, the shoe was drilled and a 10' ft rat hole with no flow being detected.

The well was placed on production in mid 2006 and it was producing oil with 0 % water cut for almost a year before observed dead due to communication that was confirmed by water sampling and PLT log as well.

WELL-C



Figure#9: Well sketch for well-C

3.4 Well-D 485 (Horizontal Open Hole Producer):

3.4.1 Drilling:

This well was drilled and completed as an Arab-D vertical open hole producer in late 2007. In this well, an 8-1/2" open hole was drilled from two formations above Arab-A all the way down to 2' TVD above Arab-D zone-1 reservoir with full circulation. Mud weight was 64 pcf at start till Arab-C formation was hit when well started flowing at 25 BPH with H₂S traces. The mud weight was raised to 80 pcf to kill Arab-C formation. After that, the rest of hole was drilled to Arab-D reservoir. The hole was swept with viscous pill to effectively clean the well by improving cutting lifting efficiency. In addition, a wiper trip was performed from the bottom up to 9-5/8" casing shoe to boost hole cleaning efficiency before running the 7" liner.

3.4.2 Running and cementing 7" production Liner:

7" liner was run consisting of Float Shoe, Float Collar, Landing Collar, 7" casing Joints and mechanical hanger along with Top Packer and tie back Receptacle. The liner was centralized as follows;

Every single joint till the angle of 45 degrees and then every second joint KOP were centralized with glider Centralizers and above that every third joint was centralized to 9-5/8" casing shoe with collapsible centralizer followed by every third joint centralized inside casing to 7" liner hanger using a bow rigid centralizer.

Upon reaching the bottom, the casing was rotated and reciprocated besides circulating the well at the highest possible rate in order remove mud cake. Then, the mechanical liner hanger was set. After that, water spacer was pumped ahead of cement in order to remove any residual impurities and prevent any potential cement contamination if it gets in contact with mud. Then, the well was cemented using two-stage cement as follows;

Lead Cement

Class G + 0.05 gps (Defoamer) + 0.05% (Dispersant) + 0.6% (Fluid loss) + 0.01 % (Retarder)	
Slurry weight	101 pcf
Thickening Time	5-5.5 hours
Slurry Yeild	1.69 cu ft/sack

Table#9: Lead cement recipe for well-D.

Tail Cement

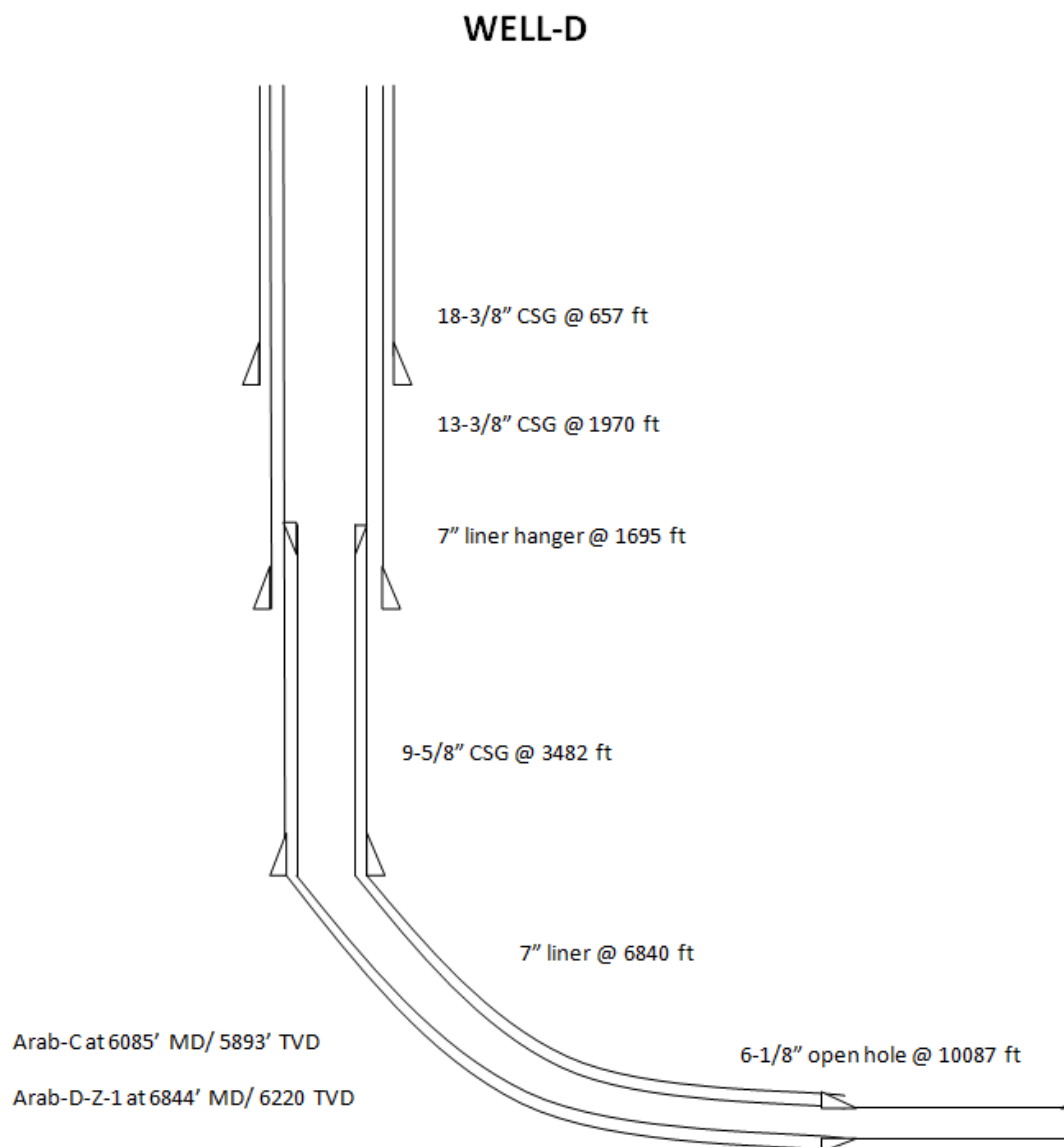
Class G + 0.05 gps (Defoamer) + 0.01% (Dispersant) + 0.25% (Fluid loss) + 0.01 % (Retarder)	
Slurry weight	118 pcf
Thickening Time	4:30– 5 hours
Slurry Yeild	1.15 cu ft/sack

Table#10: Tail cement recipe for well-D.

At first, the lead cement (light cement) was pumped followed by the tail cement (heavy cement). Then, the dart was dropped and displaced by mud until it latched the wiper plug in the liner hanger. Then, the pressure was increased to shear the wiper plug and displaced until it landed in the landing collar. No lost circulation was encountered. At the end, the excess cement was reversed out before the liner top packer was set.

After WOC time had finished, a clean out trip was performed to drill out cement inside the liner plus float equipment till 10 ft above shoe before that liner was tested with water to 2000 psi. No leak was observed. After that, the shoe was drilled and a 10' ft rat hole with no flow being detected.

Several attempts were made to kick off the well with N₂ during mid 2008 but to no avail. The well was producing mainly water. Lab analysis showed that this water was coming from Arab-C formation confirming communication between Arab-C and D.



Figure#10: Well sketch for well-D

3.5 Well-E 1586 (Vertical Cased Hole Producer):

3.5.1 Drilling:

This well was drilled and completed as an Arab-D Vertical open hole producer in late 2005. In this well, an 8-1/2" open hole was drilled from two formations above Arab-A all the way down to 2' TVD above Arab-D, zone-1 reservoir with full circulation. Mud weight was 64 pcf at start till Arab-C formation was hit when well started flowing at 25 BPH with H₂S traces. The mud weight was raised to 88 pcf to kill Arab-C formation. After that, the rest of hole was drilled to Arab-D reservoir. The hole was swept with viscous pill to effectively clean the well by improving cutting lifting efficiency. In addition, a wiper trip was performed from the bottom up to 9-5/8" casing shoe to boost hole cleaning efficiency before running the 7" liner.

3.5.2 Running and cementing 7" production Liner:

7" liner was run consisting of Float Shoe, Float Collar, Landing Collar, 7" casing Joints and mechanical hanger along with Top Packer and tie back Receptacle. The liner was centralized as follows;

The first five joints and then every second joint to 9-5/8" casing shoe were centralized with collapsible Centralizers and every third joint was centralized inside casing to 7" liner hanger using a bow rigid centralizer.

Upon reaching the bottom, the casing was rotated and reciprocated besides circulating the well at the highest possible rate in order remove mud cake. Then, the mechanical liner hanger was set. After that, water spacer was pumped ahead of cement in order to remove any residual impurities and prevent any potential cement contamination if it gets in contact with mud. Then, the well was cemented using two-stage cement as follows;

Lead Cement

Class G + 0.65% (Fluid loss) + 0.35% (Dispersant) + 0.01 gps (Retarder) + 0.01 gps (Defoamer)	
Slurry weight	118 pcf
Thickening Time	5 hours
Slurry Yield	1.15 cu ft/sack

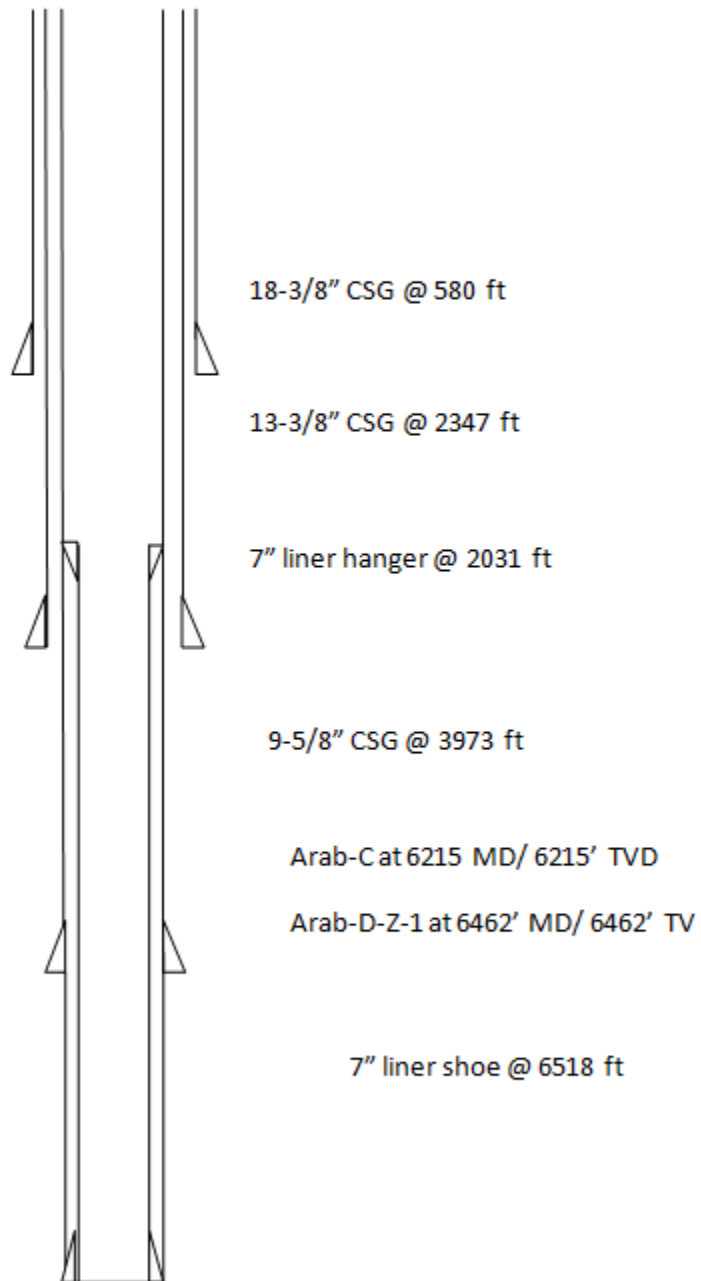
Table#11: Lead cement recipe for well-E.

At first, the lead cement (light cement) was pumped followed by the tail cement (heavy cement). Then, the dart was dropped and displaced by mud until it latched the wiper plug in the liner hanger. Then, the pressure was increased to shear the wiper plug and displaced until it landed in the landing collar. No lost circulation was encountered. At the end, the excess cement was reversed out before the liner top packer was set.

After WOC time had finished, a clean out trip was performed to drill out cement inside the liner plus float equipment till 10 ft above shoe before that liner was tested with water to 2000 psi. No leak was observed.

The well was placed on production in mid 2006 and it was producing oil with 0 % water cut for almost a year before observed dead due communication that was confirmed by water sampling and PLT log as well.

WELL-E



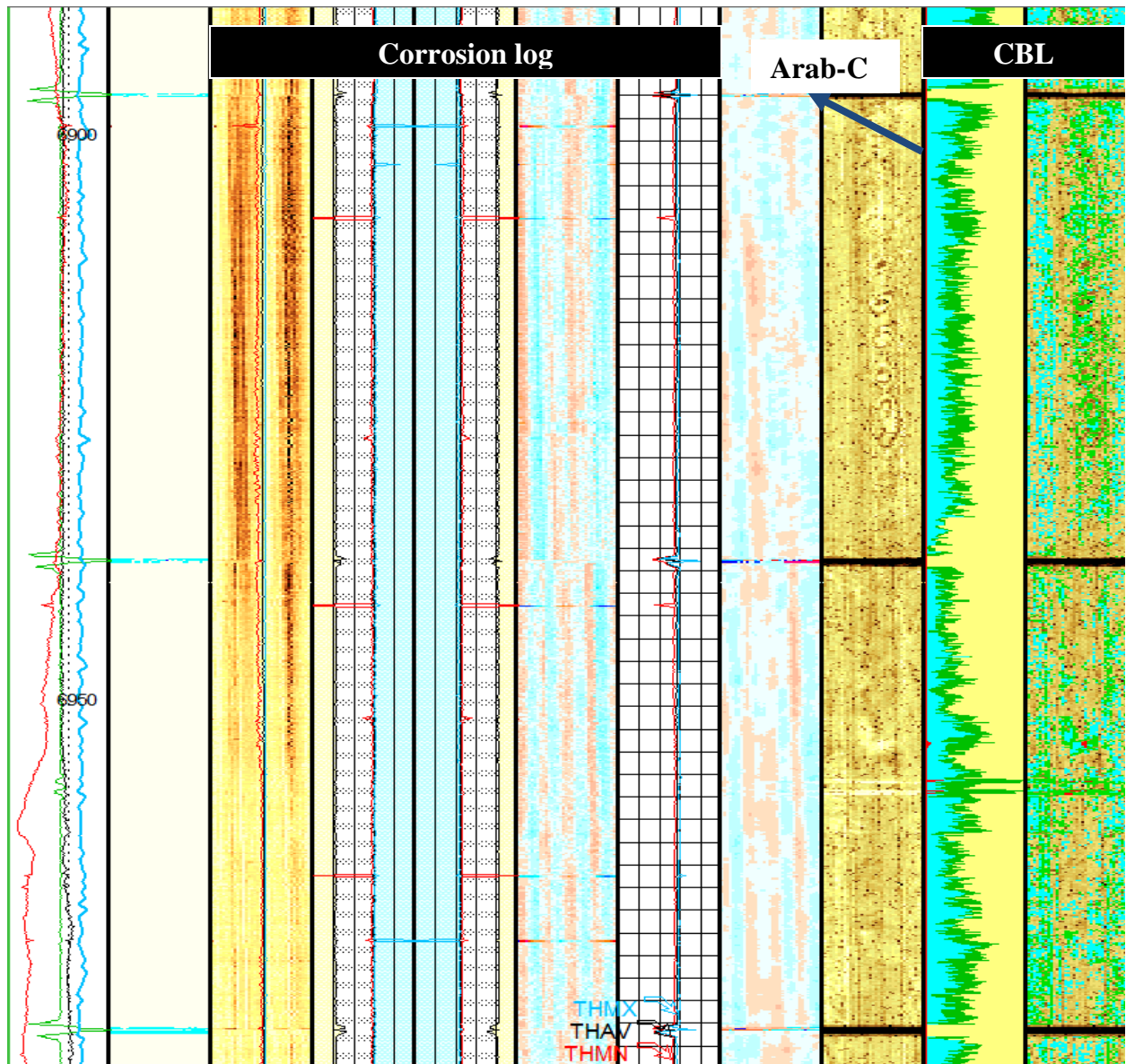
Figure#11: Well sketch for well-D

3.6 Cased Hole logs:

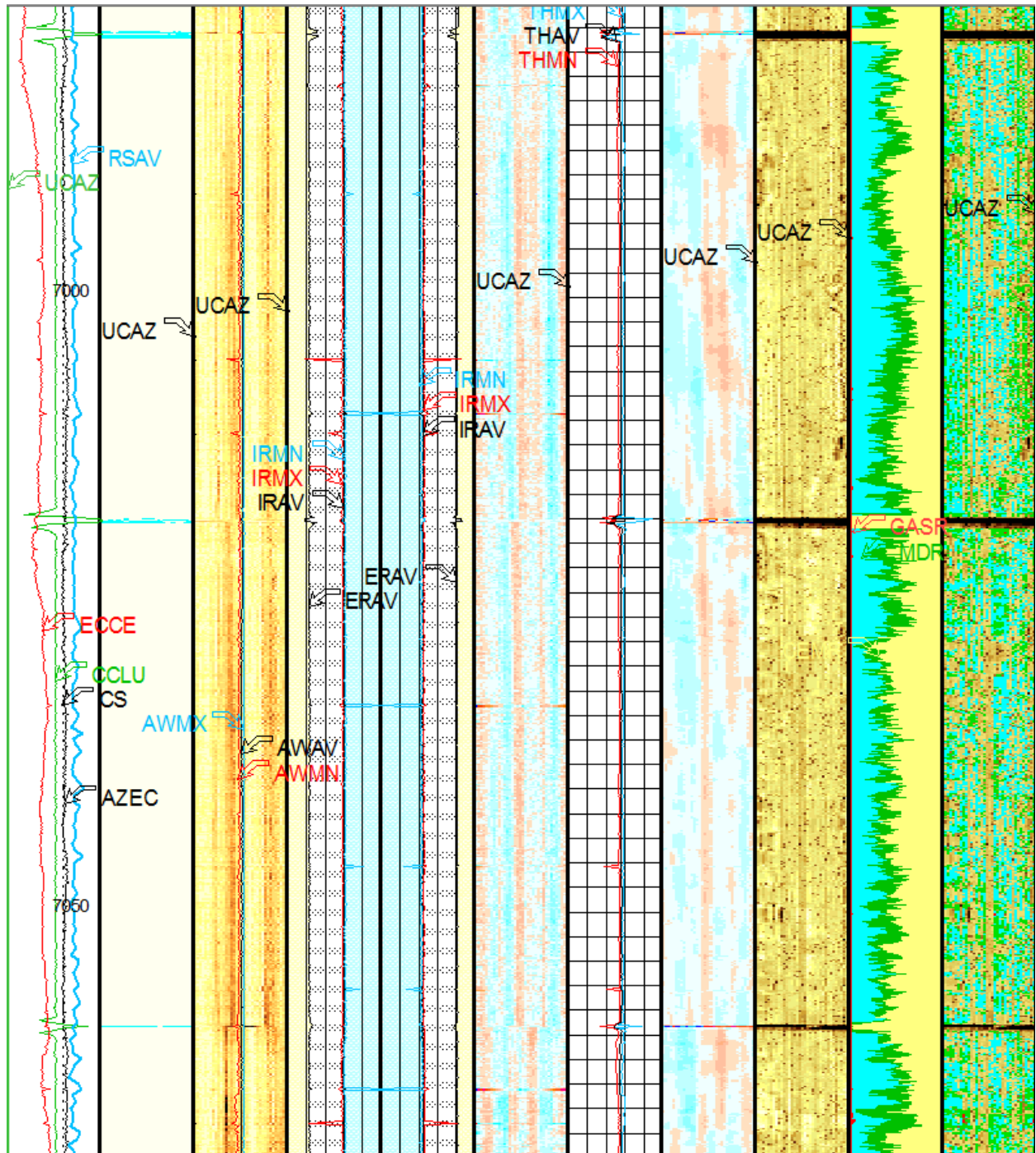
Six months after putting those wells on production, Arab-C formation started flowing water. A water sample was collected and tested. Lab test showed that the water is Arab-C water. Further measure was taken to keep track of water rout. Therefore, cement evaluation logs were run in most wells. Logs of three wells will be analyzed only in this report as all of them have the same results. The CBL was run in conjunction with corrosion log that measures the internal and external radii of the casing and VDL (variable density log). In our study, we will concentrate only on CBL log that quantifies the quality of cement. Basically, it represents the cement bond in three colors; green, blue and yellow. The green color refers to hydrocarbon; blue color demonstrates water and yellow color represents cement.

3.6.1 WELL-A

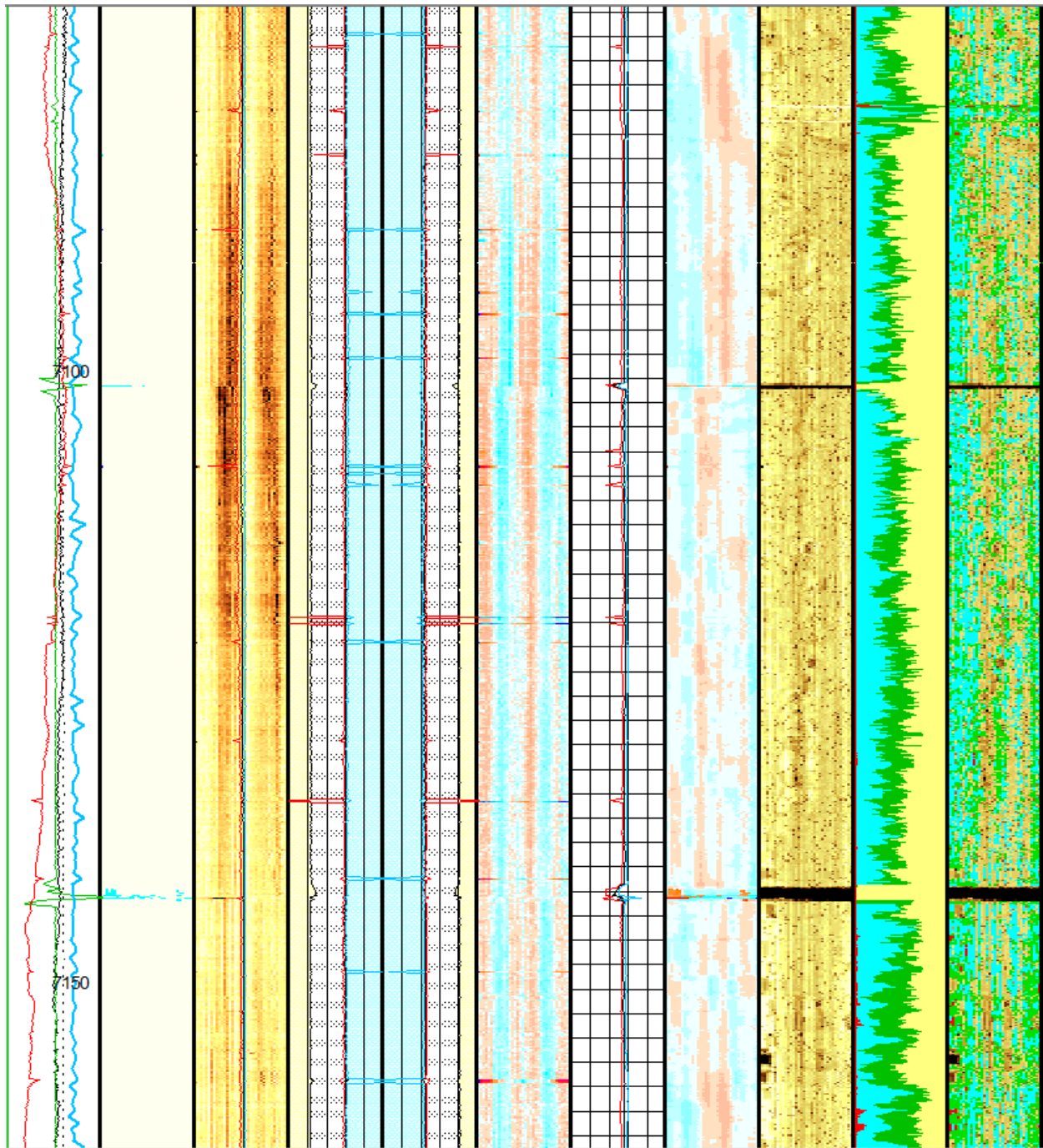
CBL log was run across Arab's formations to evaluate cement between Arab-C and D formations.

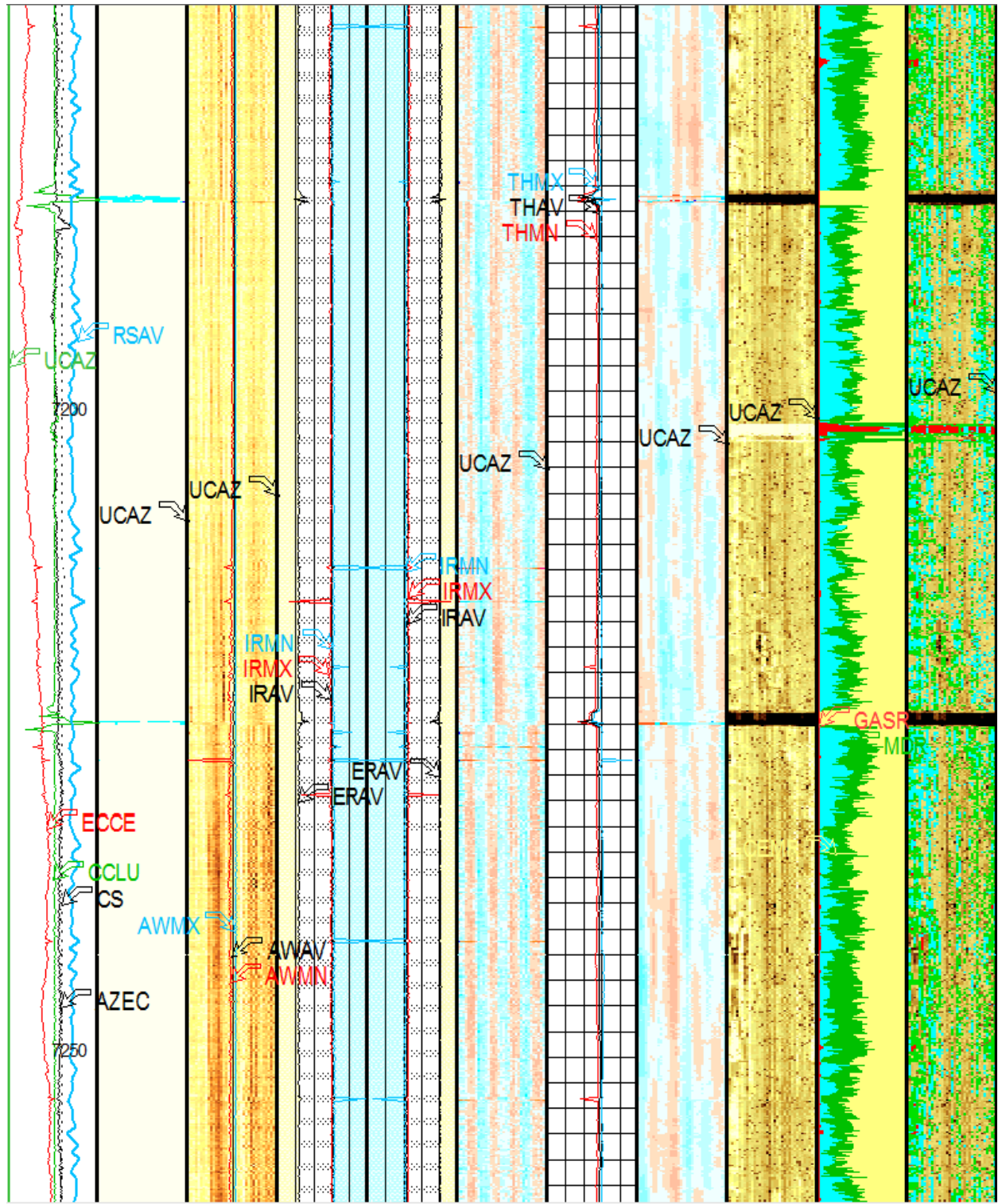


Figure#12: CBL for well-A from 6875 ft to 6975 ft

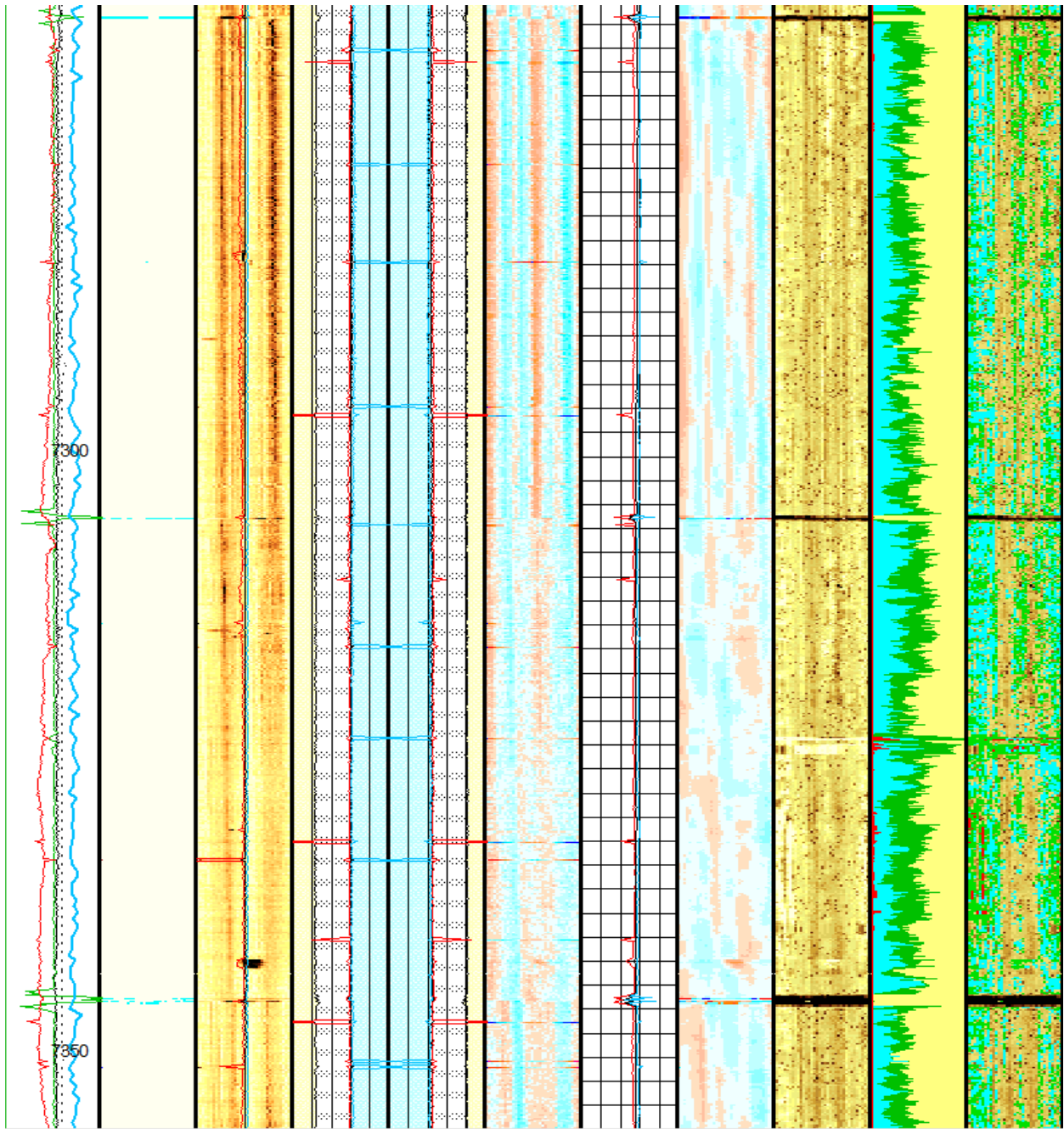


Figure#13: CBL for well-A from 6975 ft to 7075 ft

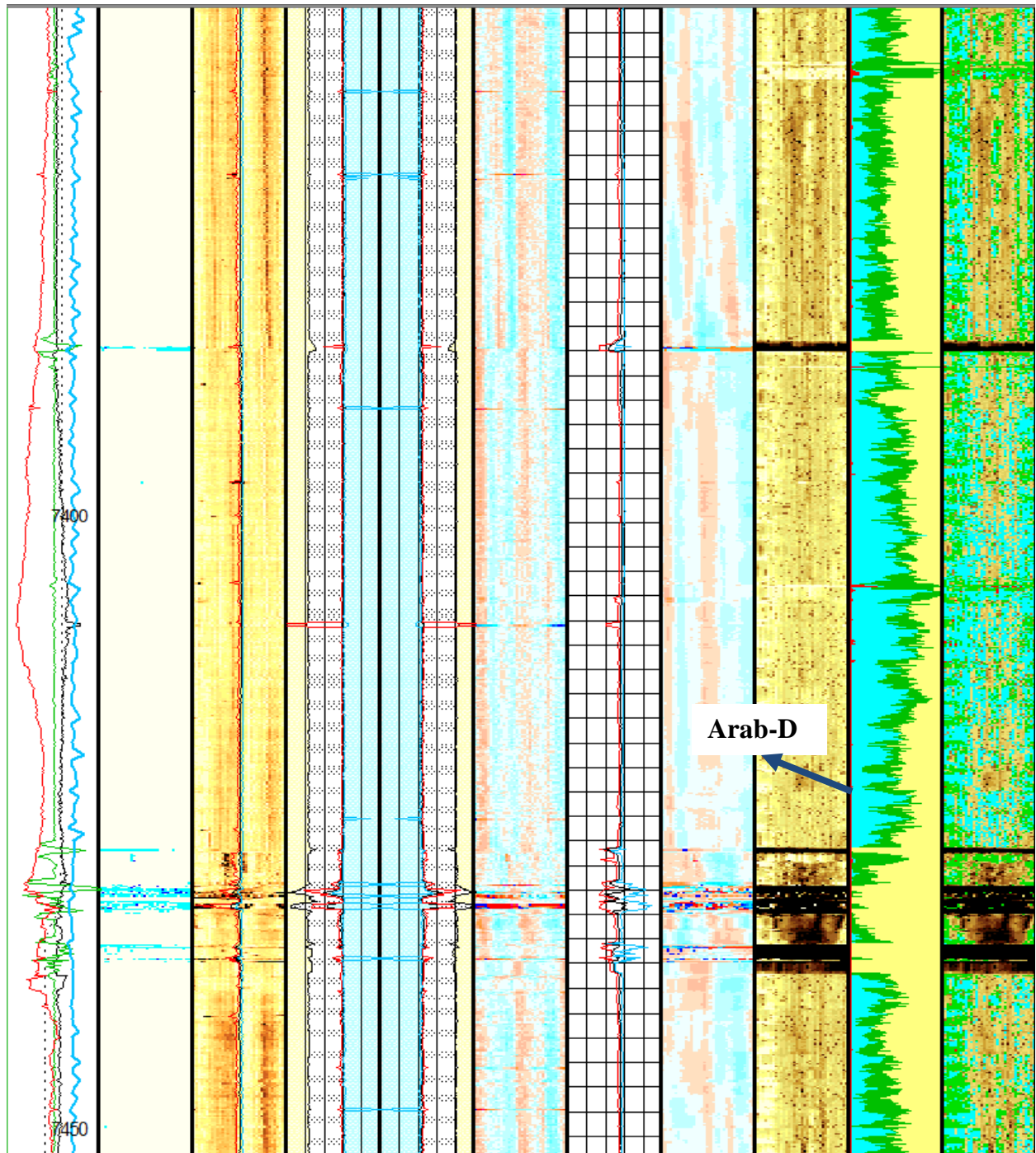




Figure#15: CBL for well-A from 7075 ft to 7275 ft



Figure#16: CBL for well-A from 7275 ft to 7375 ft

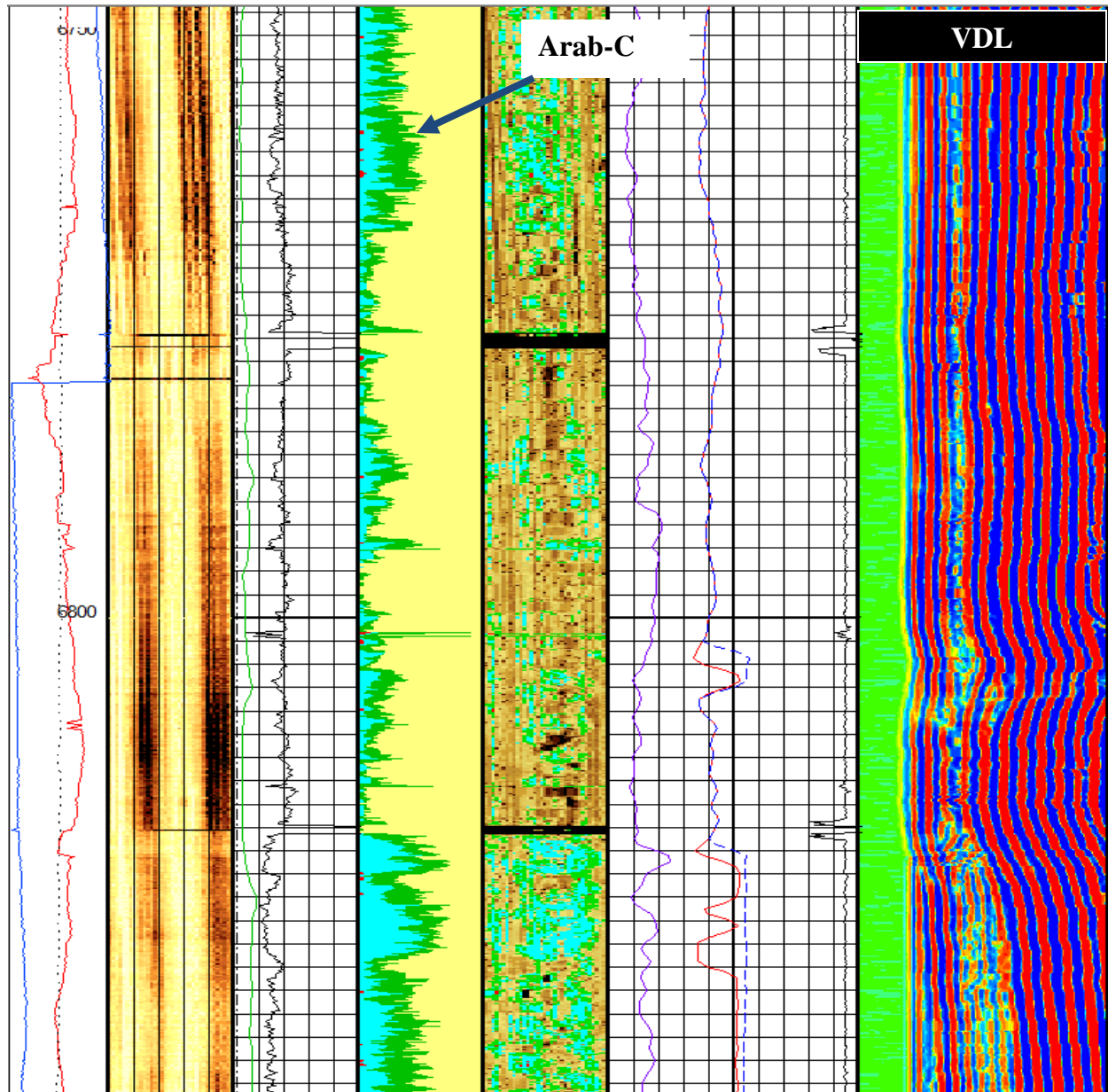


Figure#17: CBL for well-A from 7375 ft to 7455 ft

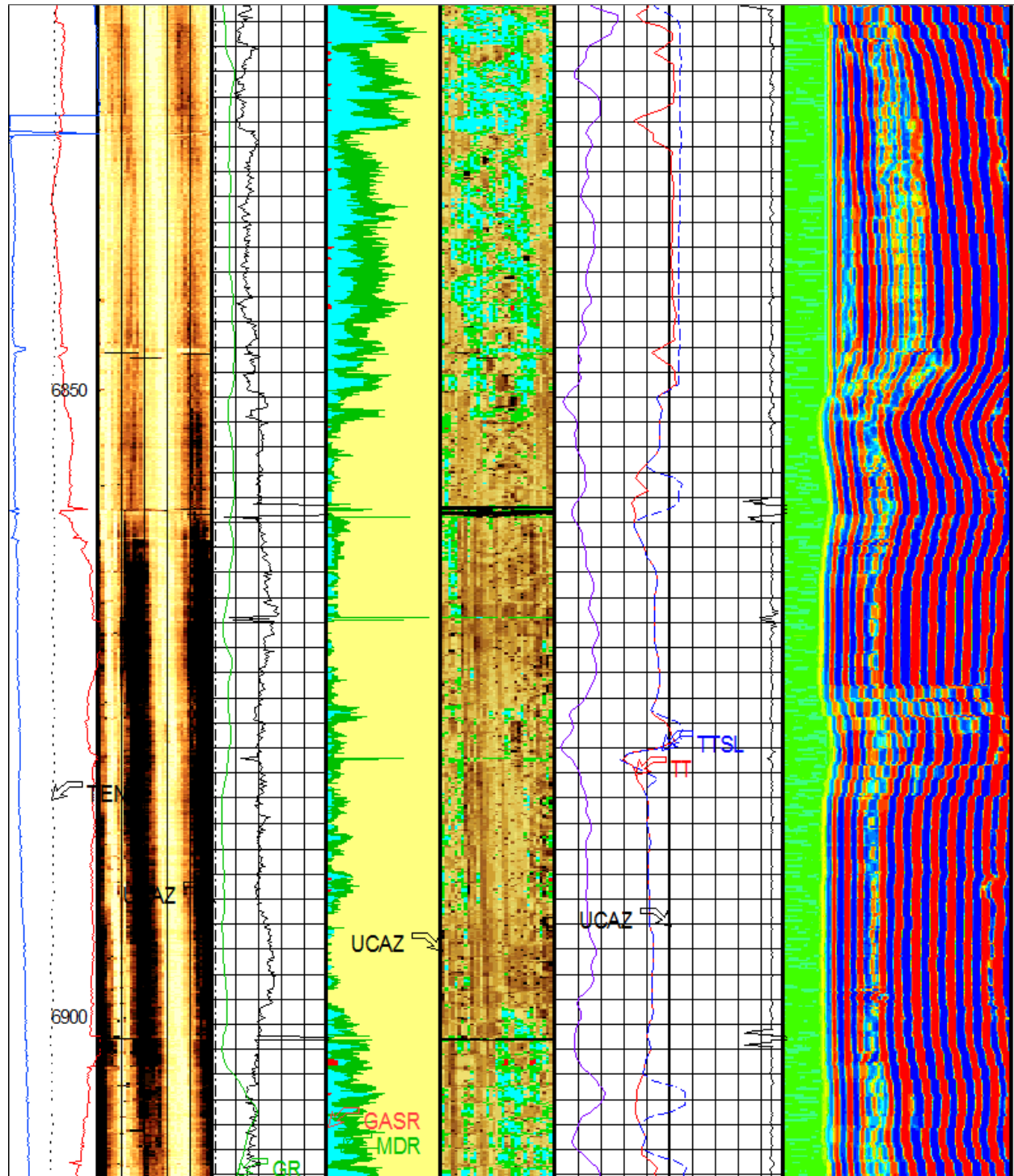
According to the log above, there was poor cement behind the liner. In addition, there is a continuous water channel. This was clearly an evidence that communication has established between Arab-C and D zones.

3.6.2 Well-B

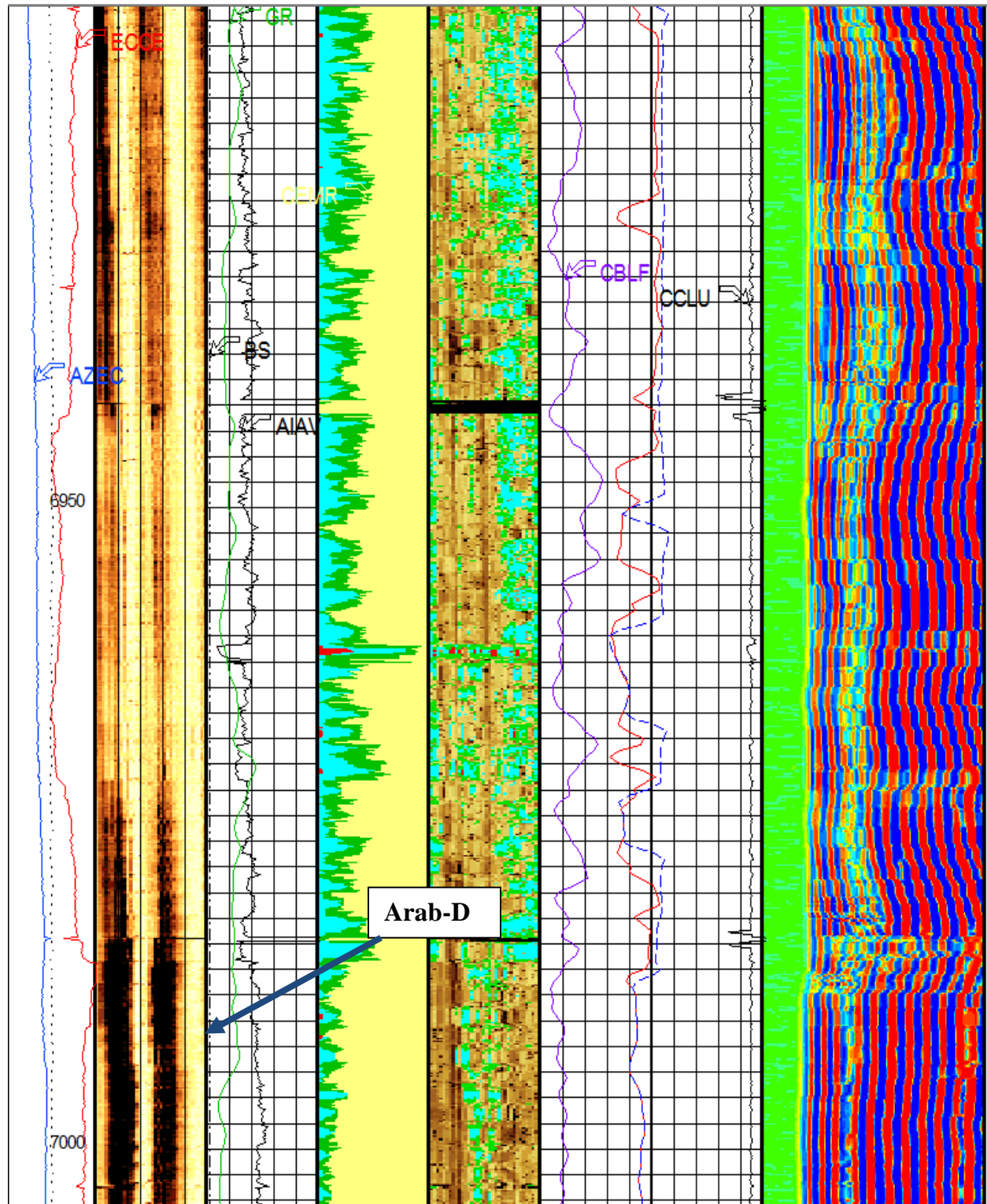
CBL log was run across Arab's formations to evaluate cement between Arab-C and D formations.



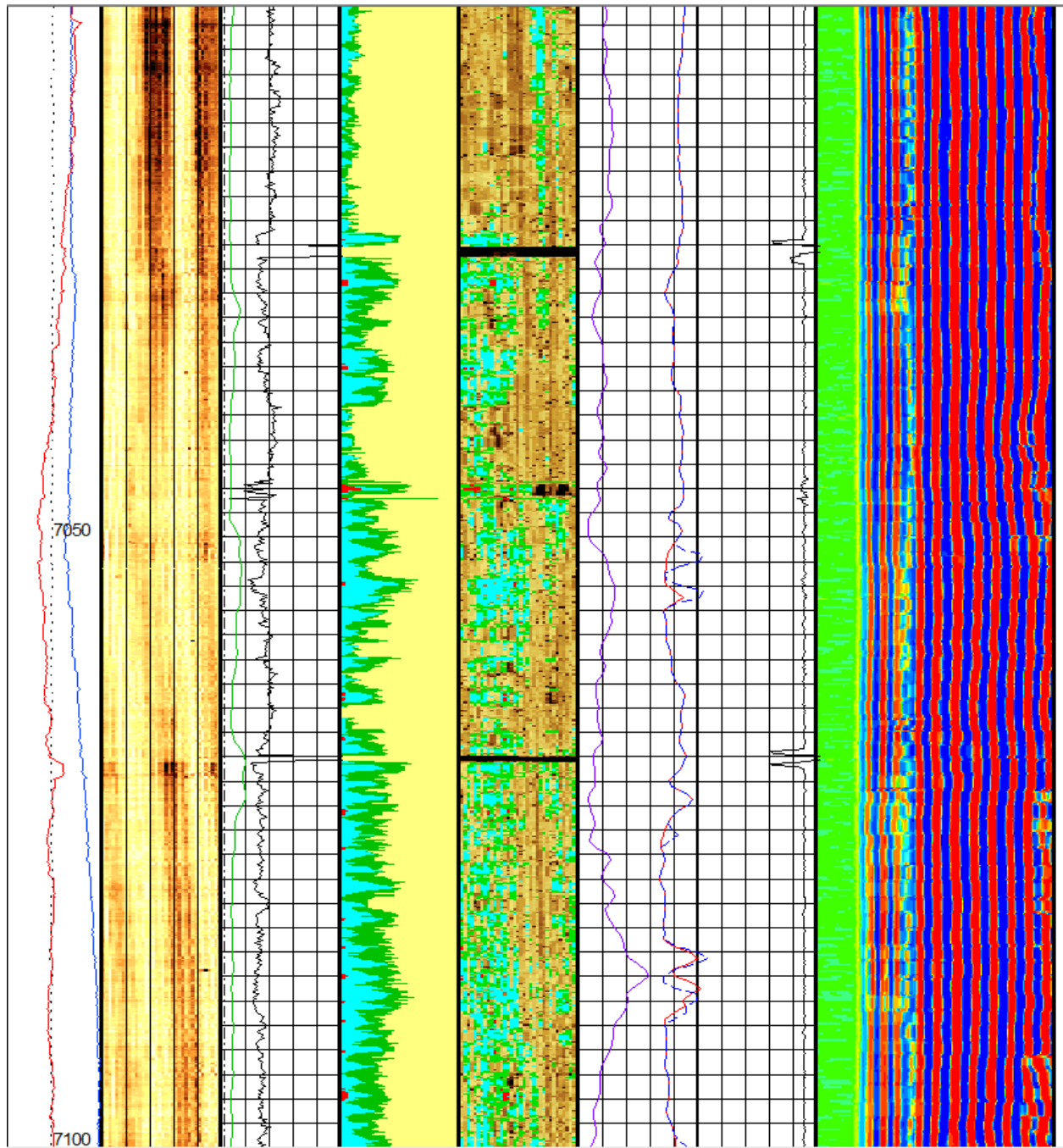
Figure#18: CBL for well-B from 6750 ft to 6825 ft



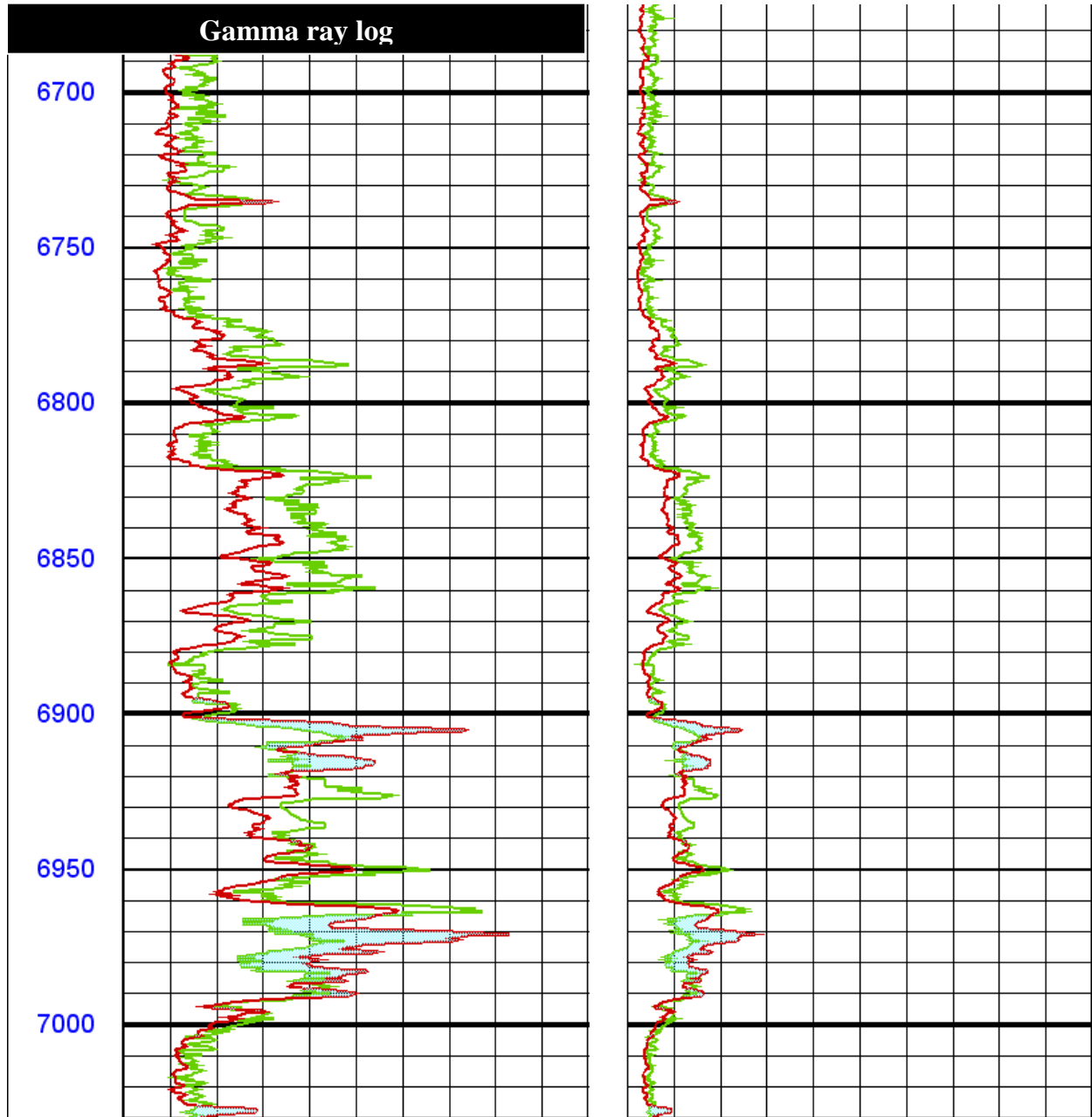
Figure#19: CBL for well-B from 6825 ft to 6910 ft



Figure#20: CBL for well-B from 6910 ft to 7010 ft



Figure#21: CBL for well-B from 7010 ft to 7100 ft

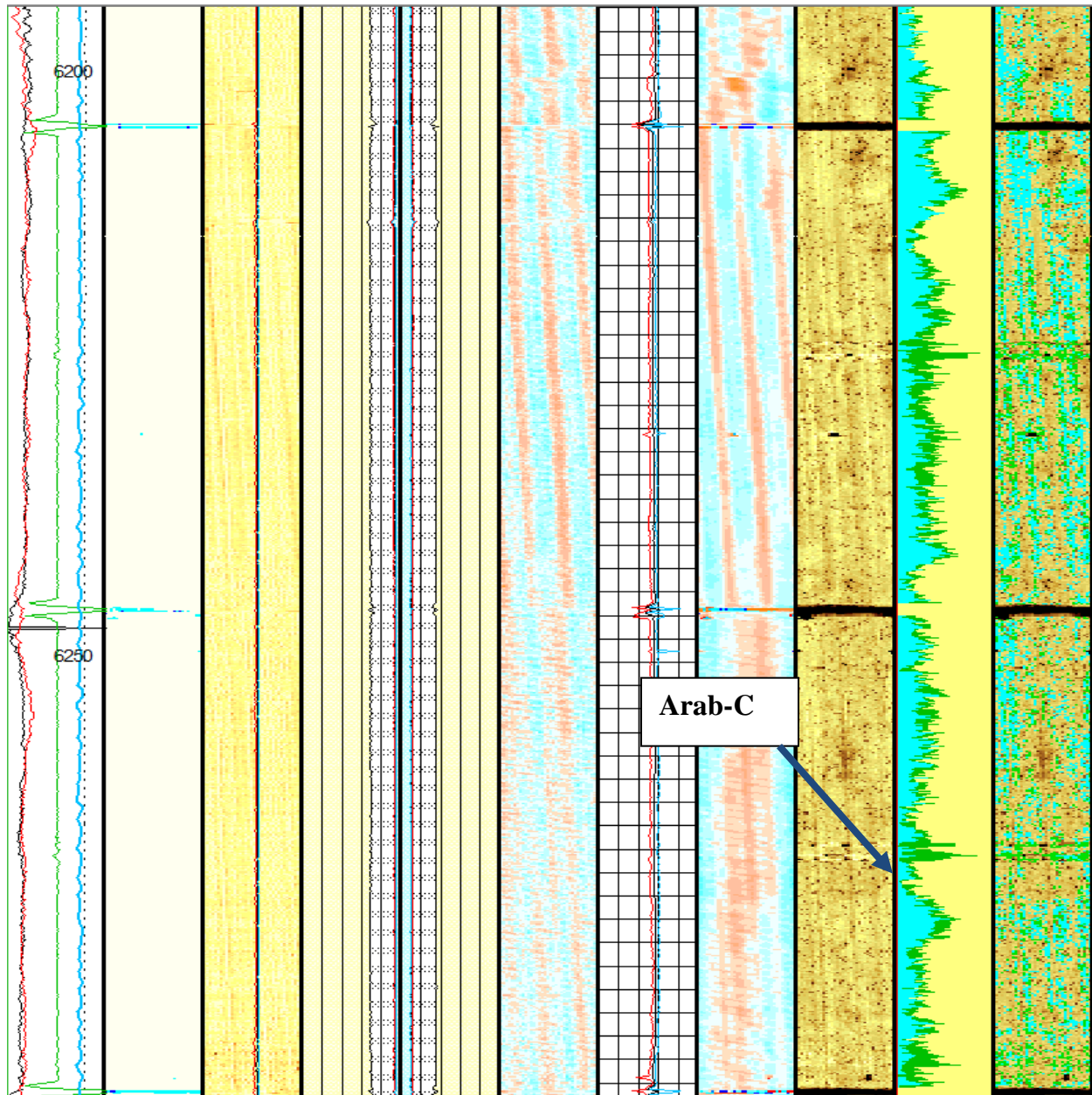


Figure#22: GR log for well-B from 6670 ft to 7030 ft

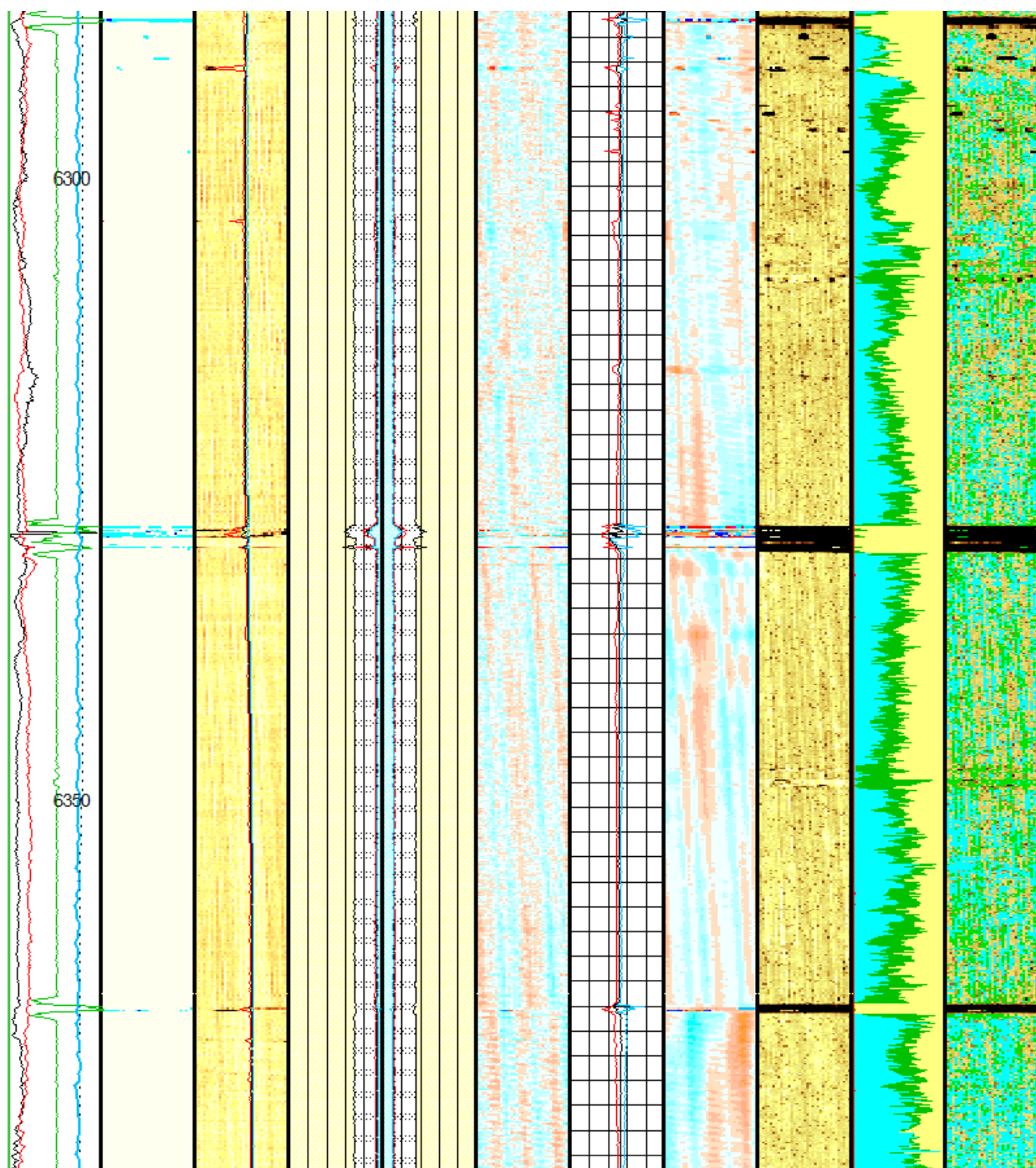
The log showed the same results as those of well-A. There was poor cement across Arab-C and D zones and a continuous water channel too. This was considered as an indication that the communication has occurred. Also, the GR log has confirmed there was cross flow between base of Arab-C and Arab-D

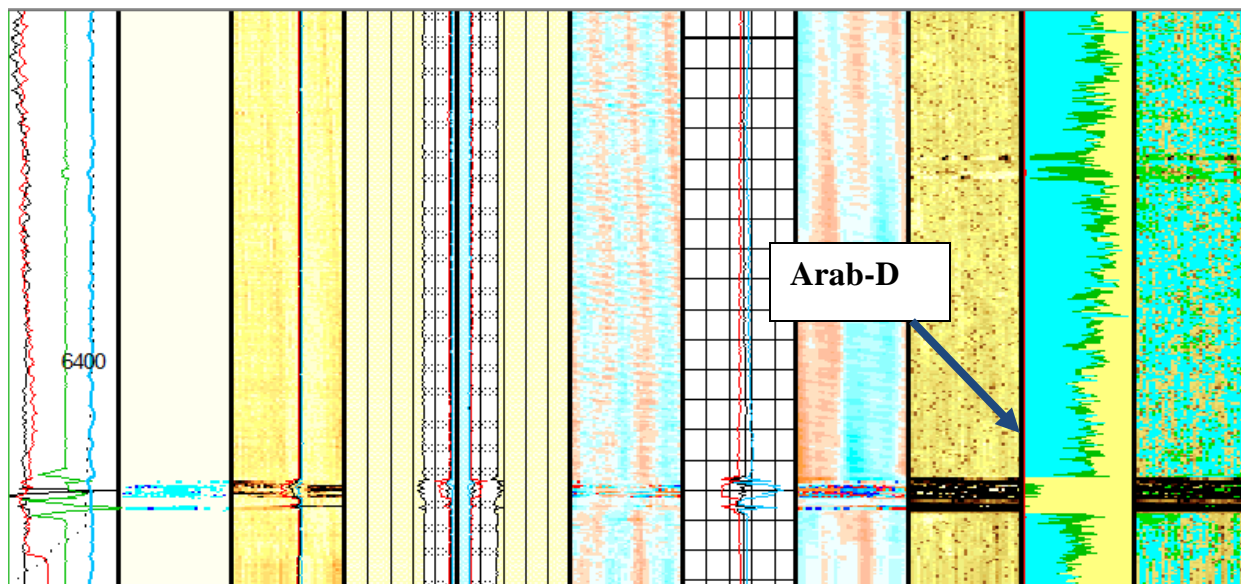
3.6.3 WELL-E:

CBL log was run across Arab's formations to evaluate cement between Arab-C and D formations.



Figure#23: CBL for well-E from 6190 ft to 6275ft





Figure#25: CBL for well-E from 6275 ft to 6375ft

The log shows there was a severe cement contamination that caused communication problem between Arab-C and D zones

Chapter 4

Effect of Sour Arab-C Water and High pressure Environment on Cement Slurry

Originally, the cement slurry was placed in harsh environment where the pressure reaches 4000 psi and CO₂ and H₂S gases exist. It is still a disputable point whether really sour conditions have contributed to poor cementing behind the liner that resulted in a communication problem between Arab-C and D. The effect of Arab-C water should not be overlooked when addressing the problem. Therefore, we will challenge the assumption that claims Arab-C water did not add to this problem at all.

Cement deterioration can be accelerated in presence of corrosive CO₂ gas. The effect of CO₂ is much worse in High Pressure-High Temperature formations. In such environment cement degradation due to carbonation will occur in short time. There are three different chemical reactions when cement is in contact with CO₂;

Formation of carbonic Acid (H₂CO₃): It lowers pH and its effect depends on temperature, partial CO₂ pressure and other ions dissolved in the water.

Carbonation of cement or cement hydrates: It causes increase in density which leads to increased hardness and decrease in permeability of cement sheath. As a result, CO₂ diffusion will decrease and volume will increase by up to 6 %. In this case, cracks will develop.

Dissolution of CaCO_3 : This phenomenon happens in the presence of water containing CO_2 and normally over long period of time. Effects of the reaction include increase in both permeability and porosity and loss of mechanical integrity. This thing will lead to poor formation isolation.

It is still disputable whether or not carbonation is detrimental to cement integrity. Some researchers showed that mechanical properties of cement will suffer degradation due CO_2 exposure leading to fluid migration. On the other hand, some studies conducted on evaluate cement in 20 to 30 year CO_2 storage wells showed that they maintained their integrity despite carbonation. Cement mainly consists of tricalcuim silicate C_3S and dicalcuim silicate C_2S . When cement reacts with water, calcium silicate hyderate C-S-H and calcium hydroxide CaCO_3 evolves. During exposure to CO_2 dissolved in water, CaCO_3 will form. This product is harmful to cement sheath at high concentration such that it cracks cement. There are two solutions to minimize carbonation effect and prolong life of cement;

- Reducing cement permeability so that it withstand well operations with low dehydration volume shrinkage.
- Optimize cement design so that dehydration products will have lower amount of materials that are reactive with CO_2 .

A three month long study was conducted to find out the degree by which Arab-C water contributed to communication problem. In this study, cement was exposed to Formation-A water for three month under molded down hole conditions. Arab-C water contains 4.5% CO_2 gas and 1.28 PPM H_2S gas. The same cement used in those wells was used to

prepare cement samples. Initially, cement samples were cured in raw water at 215 °F before being exposed to Arab-C water at 215 °F and 4000 psi. In parallel to that, some of the cement samples were cured in raw water at the same conditions. Upon completion of curing process, cement samples were tested for physical properties, namely, permeability, compressive strength, Poisson's ratio and Young's modulus. Besides, TGA and EDXRF tests were conducted. A well was drilled to collect Arab-C water samples needed in this project. After hitting Arab-C, the well was lifted with a test packer isolating the zone until clean water reached the surface. 40 gallons of water were collected in total. Twenty four samples in total were prepared using the same cement recipe used in the field. Cement samples were then poured in different cubical and cylindrical moulds. These moulds were placed for two days in the curing chambers at 215 °F. After the curing period, cement samples were removed and the weight was recorded. Each test specimen was assigned a number. Four samples were tested for Mechanical properties, permeability, TGA and EDXRF after initial set.

The remaining samples were divided into two groups. The first set was cured under sour conditions in Hastelloy metal autoclaves for three months and six months while the second set was cured in raw water in autoclaves for the same period of time. At the end, cement samples were taken out of autoclaves and tested for mechanical properties, permeability, TGA and EDXRF.

4.1 Samples Preparation:

4.1.1 Mixing Cement:

Cement was mixed and prepared at cementing lab using cement mix below as follows;

- Add water to the jar.
- Add cement to water and mix it at 1200 rpm for 36 sec.
- Add and mix chemicals with cement in order individually with cement at 1200 rpm for 36 sec for each
- Pour cement into cylindrical and rectangular molds.

4.1.2 Curing Cement Samples:

All cement samples were cured at down-hole conditions with water using autoclaves. All samples were cured for almost two days before there were tested for permeability, shrinkage, rock mechanics and etc.

- Place cement samples inside the cylinder of autoclaves.
- Turn on water supply and fill cylinder with water.
- Turn on pump and raise pressure to 4000 psi.
- Set temperature at 210° F.
- Cure the samples for two days.
- Bleed off pressure and cool the cylinder by pumping warm water.
- Take all samples out.



Figure#26: The cement mixer



Figure#27: The cement mix



Figure#28: Cylindrical and rectangular moulds filled with cement



Figure#29: Autoclaves (curing Chamber)

4.1.3 Tagging and Numbering Samples:

Each sample was assigned a number tagged on a metal piece. The tagged number was attached to the cement sample using a wire wrap. This will help recognize samples and in turn eliminate confusion.



Figure#30: Cement sample#116



Figure#31: Cement sample#127



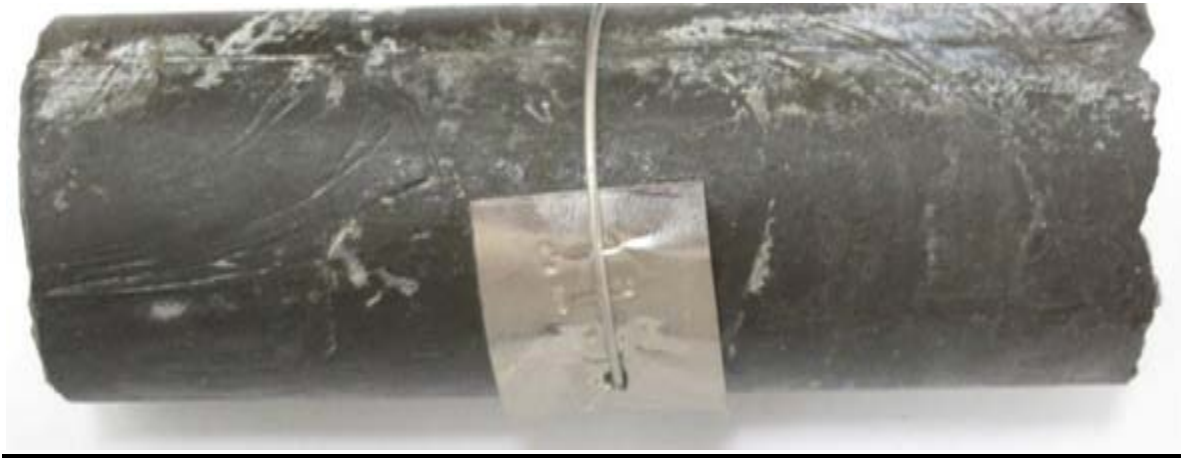
Figure#32: Cement sample#117



Figure#33: Cement sample#113



Figure#34: Cement sample#114



Figure#35: Cement sample#115



Figure#36: Cement sample#118



Figure#37: Cement sample#129



Figure#38: Cement sample#125



Figure#39: Cement sample#130



Figure#40: Cement sample#128



Figure#41: Cement sample#126

4.2 Curing Cement at Down- hole Conditions.

After the cement samples were cured with water for two days, they were placed in corrosion autoclaves for three months. During this period of time, cement was exposed to simulated down hole conditions in wells where the problem emerged. In the test, cement was cured at 4000 psi and 215⁰ F for three months and 6 months separately with sour Arab-C water that contains H₂S and CO₂ gases.

4.3 Permeability Test:

Permeability equipment was used to test cement for permeability. The equipment consists of core holder in which cement sample is placed, fluid cylinder for fluid injection, a beaker to collect fluid if any, pump for injection purpose and personal computer to collect data. The test is carried out as follows;

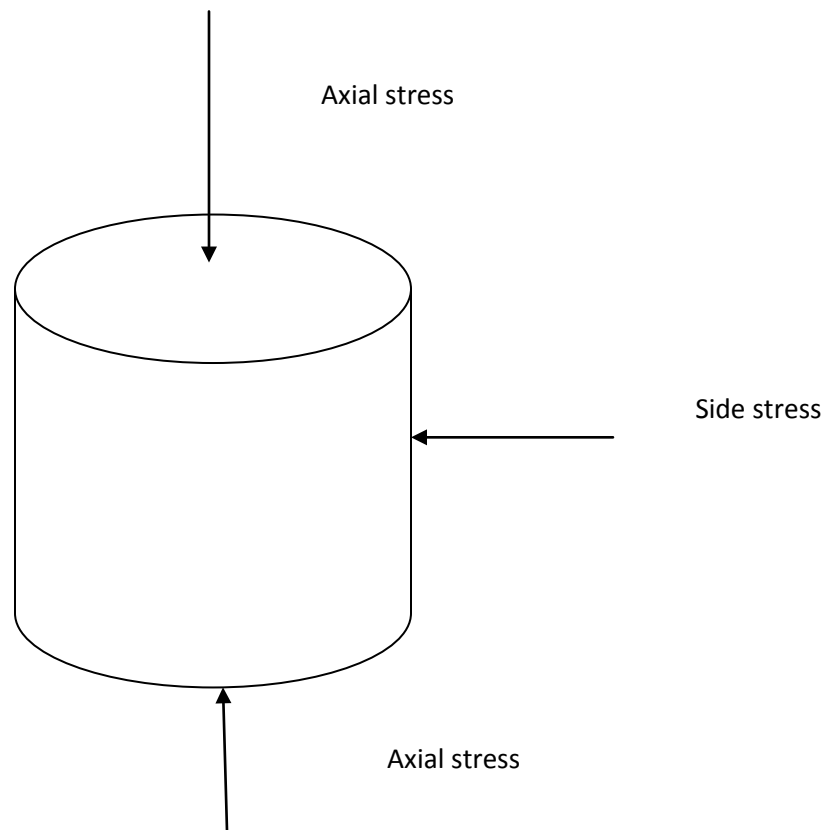
- Make sure brine cylinder is filled with proper brine composition and known viscosity, pressure transducers/gauges are calibrated, pumps are in good operational condition, and there is no leak in the flooding setup.
- Measure the diameter and length. Take three readings of diameter and length at different locations and average them (Handle plug with gloves).
- Load plug in rubber sleeve and load it in core holder.
- Apply 700 psi overburden pressure.
- Pump brine at 2 cc/min for thirty minutes.
- Wait for the pressure drop to stabilize.
- Record the steady state pressure drop if any.
- Measure the amount of fluid collected if any.
- Stop the pump, release the overburden pressure slowly.
- Remove the plug from rubber sleeve.
- Note any visible marks or damage to the plug.



Figure#42: Permeability Measurement Equipment

4.4 Rock Mechanics test

The test is conducted to calculate both Poisson ratio and young modulus to determine the axial stress at which cement starts to break down or fracture. Young modulus is the slope of the straight line relationship between stress and strain (the change of length over the original length when the sample is exposed to a force). The area under the straight line represents the elastic region when the cement can still restore its original shape. Poisson's ratio represents the change of length over the change of width that occurs when a force is applied on the cement. These two properties help quantify the degree of how hard and brittle is the cement.



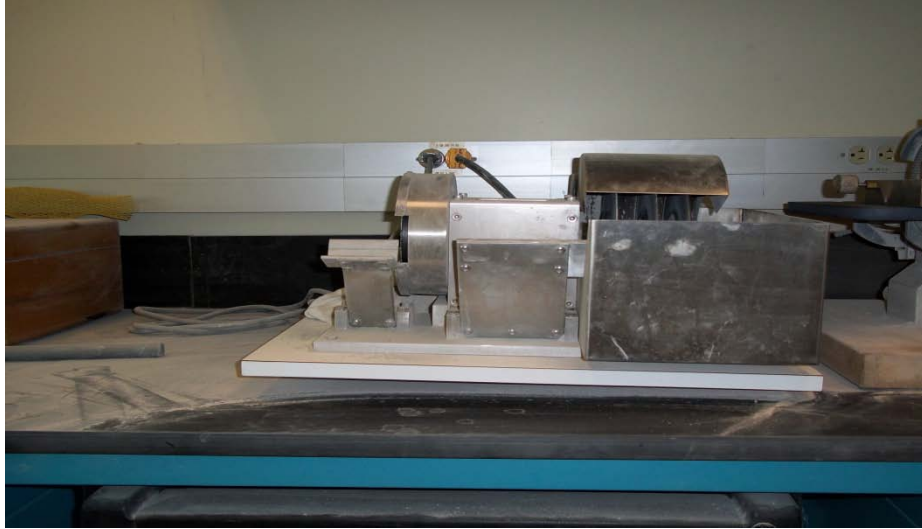
Figure#43: Forces acting on cement sample during rock mechanics test

4.4.1 Mechanical Properties Test Procedure:

- The sample is trimmed and cut to 3" X 1" size using the trimming machine.
- Surface sample is finished or ground using Surface Grinding Machine.
- Parallelism of surface of sample is measured using Parallelism equipment. It should be of 2/1000 inch to make sure the load applied by the piston is evenly distributed over the surface.
- The sample is placed inside Triaxial equipment (Basically, it consists of core holder, piston, vessel, control panel, camera and computer). At first, a plastic jacket is used to protect the plug while applying the confining pressure by evading the entry of fluid into the plug. After that, the core placed into the core holder and then three VLDT wires (Voltage linear differential Transducer) are connected the core holder. Two wires are used to measure the axial distance change and one wire for radial distance change measurement.
- Core holder is placed inside the vessel using cylindrical base screwed in to the vessel. Fill the vessel is with oil.
- Turn on pump to pressurize the system to the required confining pressure.
- Apply axial load to samples using a piston (the reading is taken at three Pressures; 5,000, 10,000 and 15,000 PA). The maximum working temperature is 150° C.



Figure#44: Grinding machine



Figure#45: Trimming machine



Figure#46: X-press machine



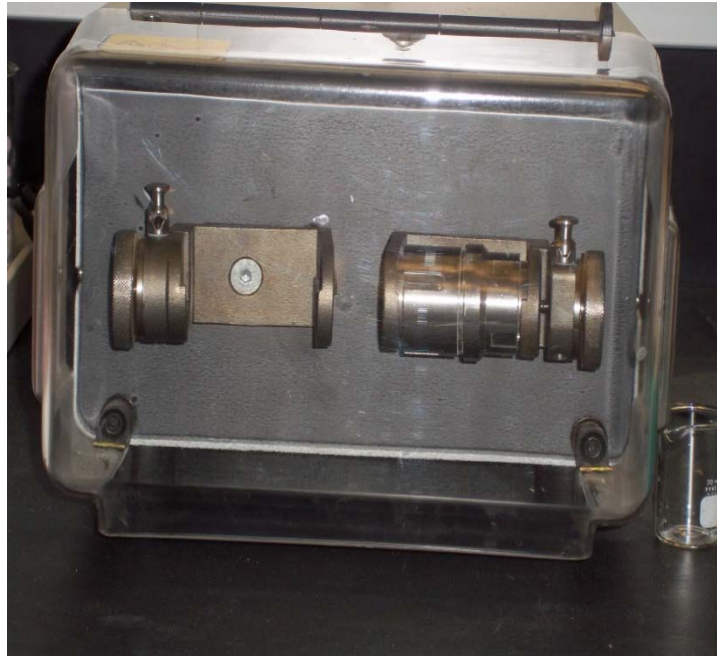
Figure#47: Triaxial measurement equipment

4.5 XRF Test:

In this test, the cement is tested to find out the elemental compositions that is to say the elements that make up the cement system.

4.5.1 Procedure:

- Grind and mill cement sample until turns completely into powder.
- Mix 5 grams of cement powder with 0.5 gram of the binder using the mixer machine for 5 minutes.
- Fill the pellet with cement powder and place it inside die of X-Press machine.
- Press the pellet with for 10 minutes under a pressure of 15 psi.
- Turn on the spectrometer (It consists of 400 watt x-ray tube, computer controlled high voltage generator for the x-ray tube, liquid N₂ cooled Si(Li) detector, multichannel analyzer and computer for data acquisition.)
- Enter the weight of sample and weight of binder.
- Place the pellet in the sample tray inside the spectrometer.
- Click on start and machine will analyze the sample for composition measurements



Figure#48: Mixing equipment



Figure#49: X-PRESS equipment



Figure#50: Cement in pellet

4.6 TGA Test:

This test is conducted to find out the effect of thermal factor on element that comprises the cement system. The effect is quantified by the weight loss that elements suffer due to heat.

4.6.1 Procedure:

- Crush and mill cement sample till becomes powder.
- Fill cement pellet with 50 mg.
- Calibrate all instruments.
- Place the sample in the machine.
- Increase temperature by 2 C/min to 1000° C.
- Wait till the system cools down.
- Remove the sample pellet

Chapter 5

Results and Discussion

5.1 Field Practices:

After an extensive review on the field practices, it is clear that the dominant factor contributing to communication between Arab-C and D formations is loss of hydrostatic pressure of cement column in addition to high Arab-C pressure. There were no deficiencies in field cementing practices including mixing and pumping cement, conditioning hole prior to Cement job, mud cake removal, mud displacement and casing centralization.

5.1.1 Mixing:

A batch mixer was used in all cement jobs as it gives the most accurate density of cement slurry.

5.1.2 Centralization:

The number of centralizers used in horizontal wells was selected to obtain 70% percent standoff across critical open hole sections. According to field findings, this degree of concentricity is fair enough for good zonal isolation. This supports that centralization was not

poor since that the problem also occurred in vertical wells where the stand-off is as high as 95%.

5.1.3 Hole Conditioning and Mud Displacement:

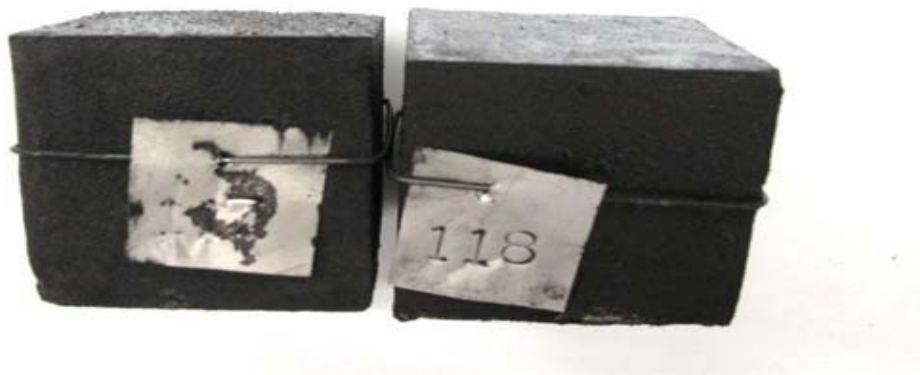
Liner rotation and reciprocation within 60' stroke in addition to circulation at rate of 4 BPM helped clean filter cake and provide uniform cement distribution around casing. Conditioning mud to reduce its viscosity improve mud displacement efficiency through enhancing fluid mobility. In addition, liner rotation and reciprocation increases mud ability to erode and remove bypassed mud by reducing casing to mud and wellbore to mud drag forces. The presence of spiral centralizer improved the flow regime of cement across horizontal sections. A compatible viscous spacer was used to separate cement and drilling fluid. The spacer helps avoid premature setting of cement, cement channeling and cement contamination. The volume of spacer was calculated to give a contact time of 10 minutes which is considered one of the widely used cementing practices. The spacer density was higher than mud and lighter than cement. This best cementing practices helps effectively displace mud and avoid mud bypassing cement.

5.2 Effect of Arab-C water on Cement:

5.2.1 Short term Test:

All samples were examined physically upon removal from the CO₂ autoclave. All samples were inspected and were found to be intact. All samples were found to have turned to a black color due to the reaction with H₂S gas. Mechanical properties including permeability, Young's modulus and Poisson's ratio were all calculated before and after Arab-C water exposure. According to permeability test, the cement stayed solid for 15 minutes during brine injection at pressure of 700 psi indicating that it is impermeable. Also, results showed there is slight change in the rest of mechanical properties. For example, static ν increased from 2.322E+06 to 2.400E+06 psi while Dynamic ν increased 2.930E+06 to 3.001E+06 psi. In regard with E, tests showed that Static E increased after exposure from 0.125 to 0.29 and Dynamic ν increased from 0.282 to 0.290. The static Poisson ratios of rocks increase with the pressure both under simple and under hydrostatic compression. The harder the rock, the less does the Poisson ratio ν depend on the load. Increased moisture content increases the static Poisson ratio. The greater the moisture content, the greater is the influence of load on the Poisson ratio. The dynamic Poisson ratio is very much less sensitive to moisture than the static one. Both under simple and hydrostatic compression, the dynamic Poisson ratio have a high value which agrees with the results of static tests at very high pressures. All results pertaining to mechanical properties tests for all samples are in tables# 12 and 13.

TGA analysis listed in table#14 showed that cement lost approximately 13% of mass due to moistures evaporation between 0 to 150 °C. Cement sample suffered further weight loss of 13 % as temperature rose to 1000 C due to decay of some elements. The sample mass decreased by 26 % in total during the test. EDXRF results tabulated in tables#15 and 16 showed that cement samples after initial curing mainly consist of 60% of CaO and SiO₂ 19% by weight. After curing in Arab-C conditions, less than 1% changes in mass occurred due to error in cement weight measurement.



Figure#51: Some cement samples after short term exposure to Arab-C water.



Figure#52: Some cement samples after short term exposure to Arab-C water

	Initial Curing		3 months Arab-C water Curing	
	Sample- 11	Sample-12	Sample-113	Sample-114
Compressive Strength psi	8,609.1	10,024.8	11,279.9	12,270.0
Dynamic E psi	2.949E+06	2.930E+06	3.025E+06	3.001E+06
Static E psi	7.153E+05	2.322E+06	1.958E+06	2.400E+06
Static v	0.282	0.281	0.174	0.219
Dynamic v	0.125	0.125	0.290	0.258

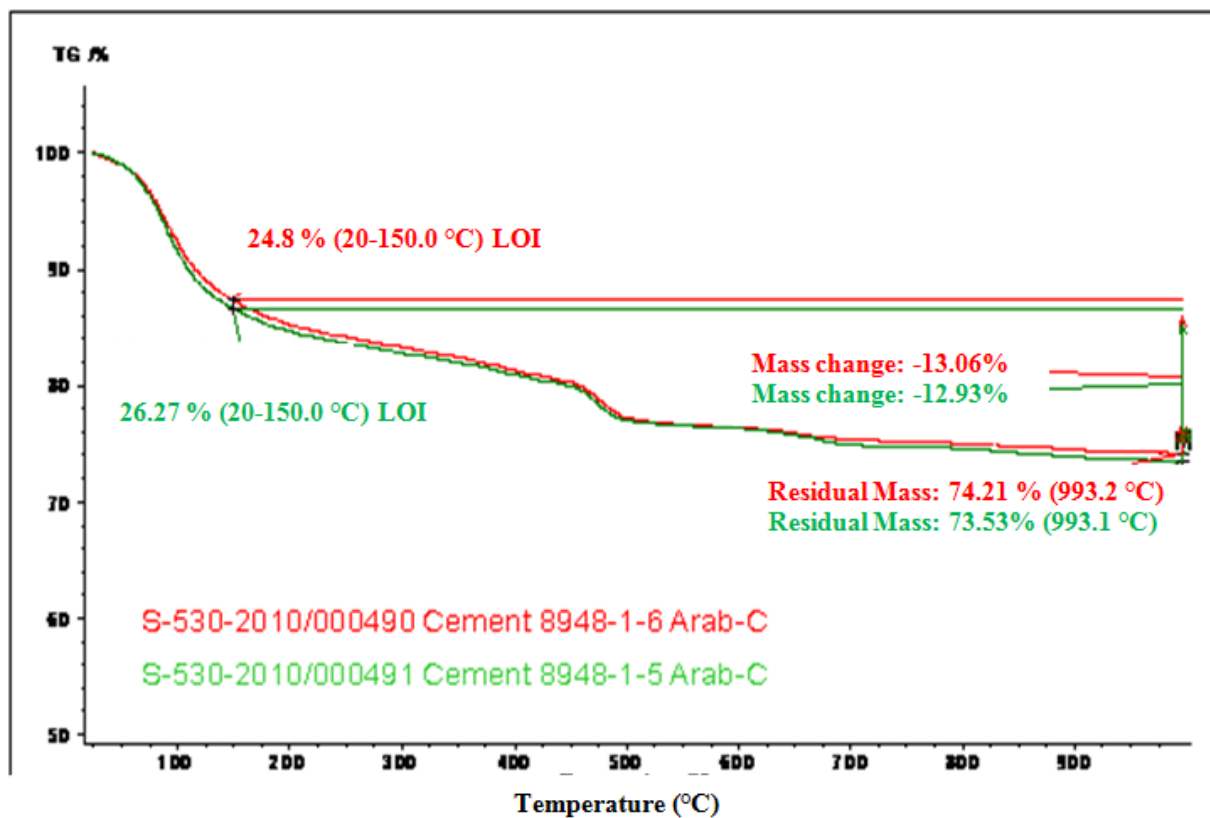
Table#12: Mechanical properties of cement samples.

	Initial Curing		3 months Arab-C water Curing	
	Sample-13	Sample-114	Sample-115	Sample-116
Permeability CC/min	0	0	0	0

Table#13: Permeability tests results of cement samples.

	Initial Curing		Short term CO ₂ Curing	
Sample#	116	115	117	118
Mass loss %	13.06	12.98	16.42	16.09
Residual Mass % (150-1000 °C)	74.21	73.57	77.59	77.57
LOI % (20-150 °C)	25.8	26.4	22.41	22.43

Table#14: TGA results after initial setting, water curing and Arab-C water curing



Figure#53: TGA chart for after initial curing

Elements	Approximate Weight Percentages	
	8948 1-5 (Initial Curing)	8948 1-6 (Initial Curing)
CaO	60.12	60.30
SiO ₂	19.85	19.76
Fe ₂ O ₃	4.52	4.54
Al ₂ O ₃	2.68	2.74
SO ₃	1.89	1.88
MgO	1.87	1.93
K ₂ O	0.43	0.46
TiO ₂	0.20	0.20
Mn ₂ O ₃	0.04	0.05
SrO	0.04	0.04

Table#15: The chemical composition for cement after initial setting.

Compounds	Approximate Weight Percentages			
	8948-1-17	8948-1-18	8948-1-23	8948-1-24
CaO	58.89	59.32	60.92	60.88
SiO ₂	18.08	18.32	19.15	19.10
Fe ₂ O ₃	4.37	4.38	4.59	4.57
Al ₂ O ₃	2.50	2.54	2.52	2.51
SO ₃	2.53	2.49	1.94	1.94
MgO	1.90	1.86	1.76	1.79
K ₂ O	0.19	0.17	0.06	0.05
TiO ₂	0.19	0.20	0.21	0.21
Mn ₂ O ₃	0.04	0.04	0.04	0.04
SrO	0.06	0.06	0.04	0.04

Table#16: The chemical composition for cement after Arab-C water curing and raw water curing

5.2.2 Long term test

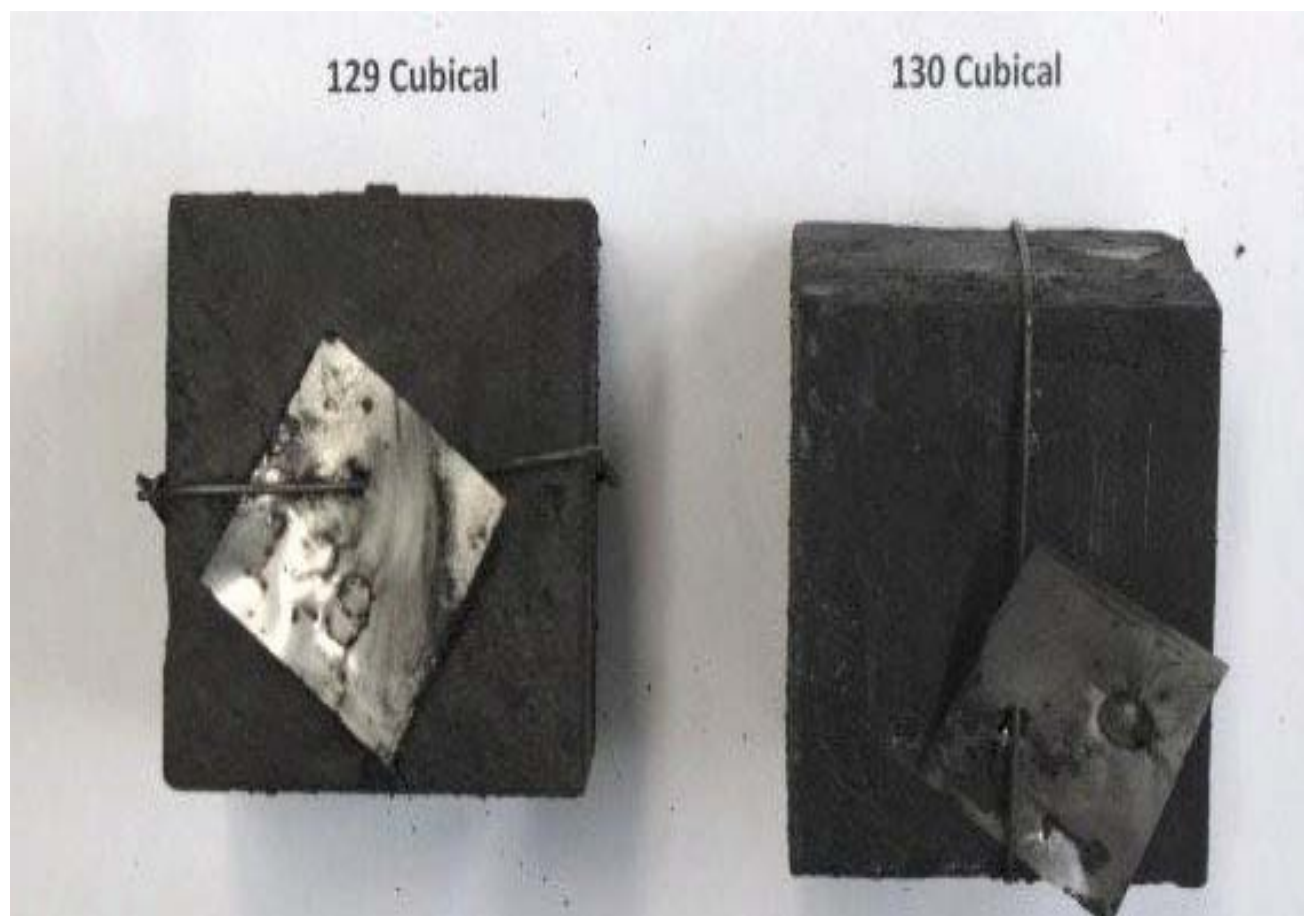
According to permeability test, the cement stayed solid for 15 minutes during brine injection at pressure of 700 psi indicating that it is impermeable. Also, results table#17 showed there is slight change in the rest of mechanical properties. For example, static ν increased from 1.089 E+06 to 2.005 E+06 psi while Dynamic ν increased from 2.998E+06 to 3.142E+06 psi. In regard with E, tests showed that Static E decreased from 0.228 to 0.189 and Dynamic ν decreased from 0.276 to 0.172.

TGA analysis in table#19 showed that cement lost approximately 4.61% of mass due to moistures evaporation between 0 to 150° C. Cement sample suffered further weight loss of 16.77 % as temperature rose to 1000° C due to decay of some elements. The sample mass decreased by 21.38 % in total during the test. EDXRF results in table#20 showed that cement samples after 6 months curing mainly consist of (60-57) % of CaO and SiO₂ (19.5-17.5%) by weight. In addition, the weight of these two elements decreased by 2 to 3 % due to an encountered error while taking the weight of cement. Besides, no major change in mass has been observed. Moreover, cement color changed from gray to black owing to reaction with H₂S gas.

These findings showed that Arab-C water did not harm cement integrity even in the presence of high pressure. This is due to the small amount of CO₂ gas present in the curing water.



Figure#54: Some cement samples after long term exposure to Arab-C water



Figure#55: Some cement samples after long term exposure to Arab-C water

	6 months Raw water Curing		6 months Arab-C water Curing	
	Sample- 117	Sample-118	Sample-125	Sample-126
Compressive Strength psi	10,944.9	11,548.6	12,656.7	13,093.8
Dynamic E psi	1.809E+06	1.816E+06	2.005E+06	1.859E+06
Static E psi	3.084E+06	2.998E+06	2.904E+06	3.142E+06
Dynamic ν	0.260	0.276	0.241	0.268
Static ν	0.242	0.288	0.189	0.172

Table#17: Mechanical properties for long term test

	Initial Curing		3 months Arab-C water Curing	
	Sample- 117	Sample-118	Sample-125	Sample-126
Permeability CC/min	0	0	0	0

Table#18: Permeability tests results for long term test.

	Long term Raw water Curing		Long term CO ₂ Curing	
Sample#	111	112	1129	130
Mass loss %	16.32	16.11	15.85	16.77
Residual Mass % (150-1000 °C)	79.09	79.49	79.59	78.62
LOL % (20-150 °C)	20.91	20.51	20.41	21.38

Table#19: TGA results after initial setting, water curing and Arab-C water curing

Compounds	Approximate Weight Percentages			
	111	112	129	130
CaO	59.85	60.06	56.96	57.90
SiO ₂	19.65	19.71	17.58	17.93
Fe ₂ O ₃	4.80	4.71	4.24	4.32
Al ₂ O ₃	2.40	2.30	2.20	2.45
SO ₃	1.88	1.89	2.39	2.38
MgO	1.70	1.68	1.66	1.88
K ₂ O	0.08	0.12	0.15	0.09
TiO ₂	0.22	0.20	0.20	0.21
Mn ₂ O ₃	0.04	0.04	0.04	0.04
SrO	<0.05	<0.05	0.07	0.06

Table#20: The chemical composition for cement after Arab-C water curing and raw water curing

5.3 Causes of Communication Problem.

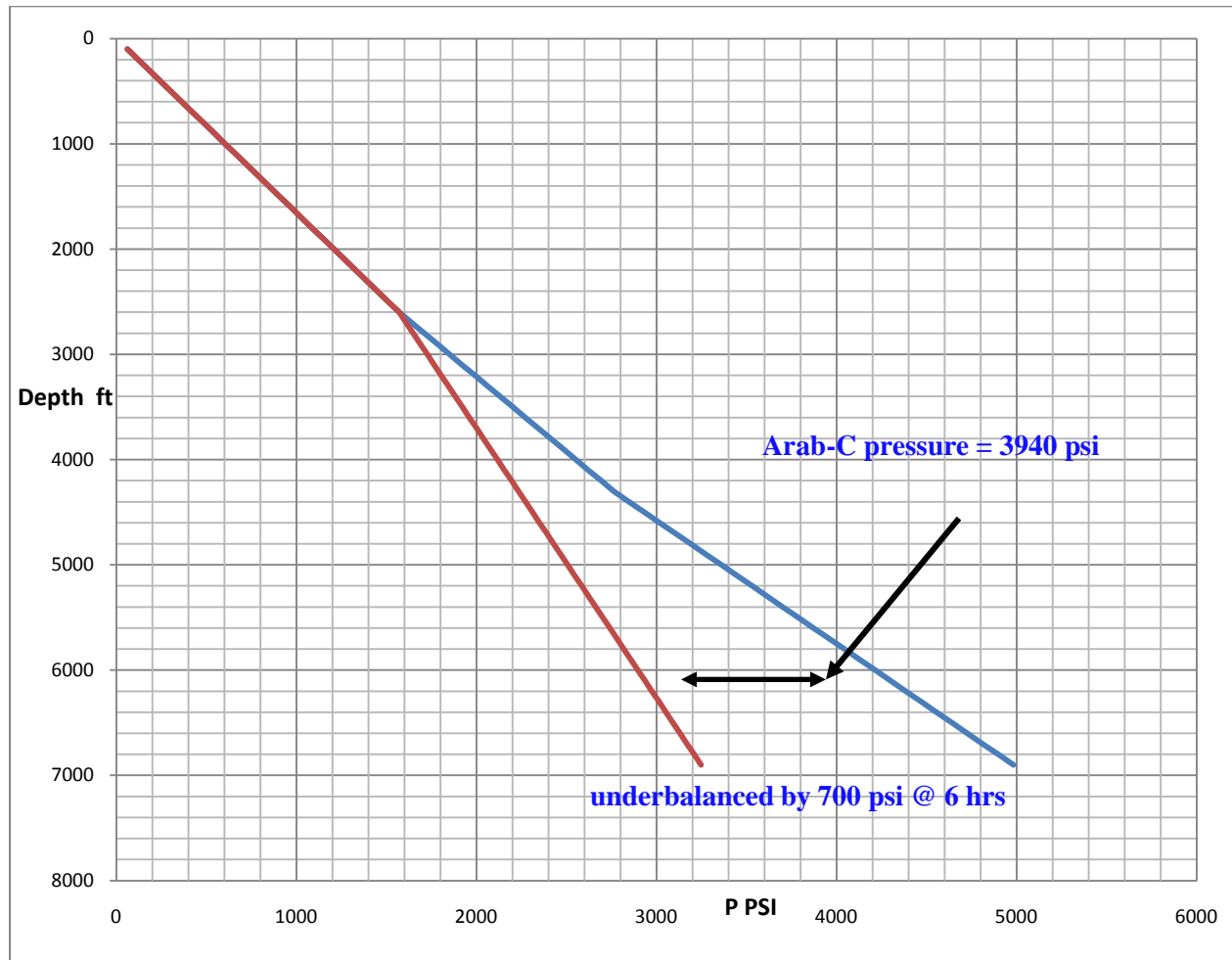
5.3.1 Reduction of Cement Hydrostatic Pressure:

The results of the review of field practices were surprising since they showed that all practices were perfect. This is not true especially when it was found that Arab-C water is not detrimental to cement. Therefore, it was imperative to go back to the literature and look in to the problem more deeply focusing on the effect of loss of hydraulic pressure while waiting on cement to set, and ignoring the other factors after it was confirmed that they are not linked to the problem completely. During the second look at the literature, an interesting experiment conducted at the field by Cooke⁽²⁾ to study the behavior of cement hydraulic pressure during

the first six hours after cement placement was found. The results of this experiment showed that cement pressure decreases at 39 psi/ft during the first six hours after pumping cement. These results are supported by the experiment Thomas conducted that showed that cement is able to transfer pressure during gelation time until cement gets set after which cement is not able to transmit pressure.

Such finding was utilized along with filed data to plot charts of pressure versus depth to study the behavior of cement hydrostatic pressure while pumping cement and six hours later. The red line up the intersection point demonstrates the pressure of mud column while the rest of it shows the pressure of cement and mud columns six hours after cement placement. In contrast, the blue line shows the pressure of cement and mud columns right after cement placement. As illustrated in the graph, the pressure at top of Arab-C pressure was 4570 psi before it decreased to 700 psi below Arab-C pressure creating an under-balance situation during which Arab-C water has displaced cement into permeable zones above and below leaving the liner none cemented and allowing communication to take place while waiting on cement to set. As a result, communication established between these two zones.

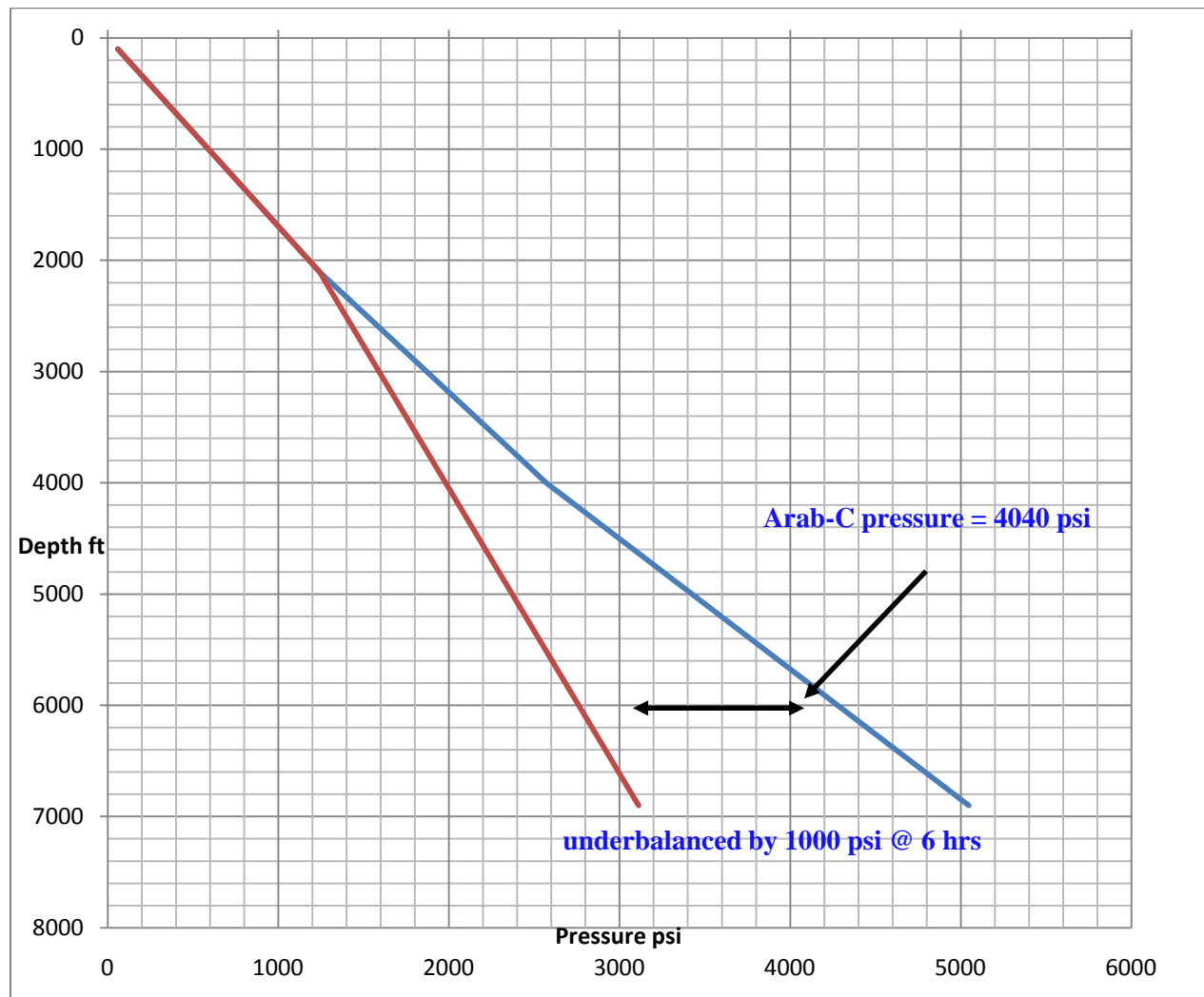
Well-A



Figure#56: Behavior of cement column pressure after 6 hrs from cement placement (well-A)

Communication between Arab-C and D formations has occurred as cement failed to develop enough compressive strength before the pressure of cement fell down below Arab-C pressure. It is clear from the graph that cement pressure had encountered a high drop in pressure of 700 psi while waiting on cement.

Well-B



Figure#57: Behavior of cement column pressure after 6 hrs from cement placement (well-B)

After the first six hours following the cement placement, the hydrostatic pressure of cement column dropped by 1000 psi creating under-balance situation and allowing for communication between formations.

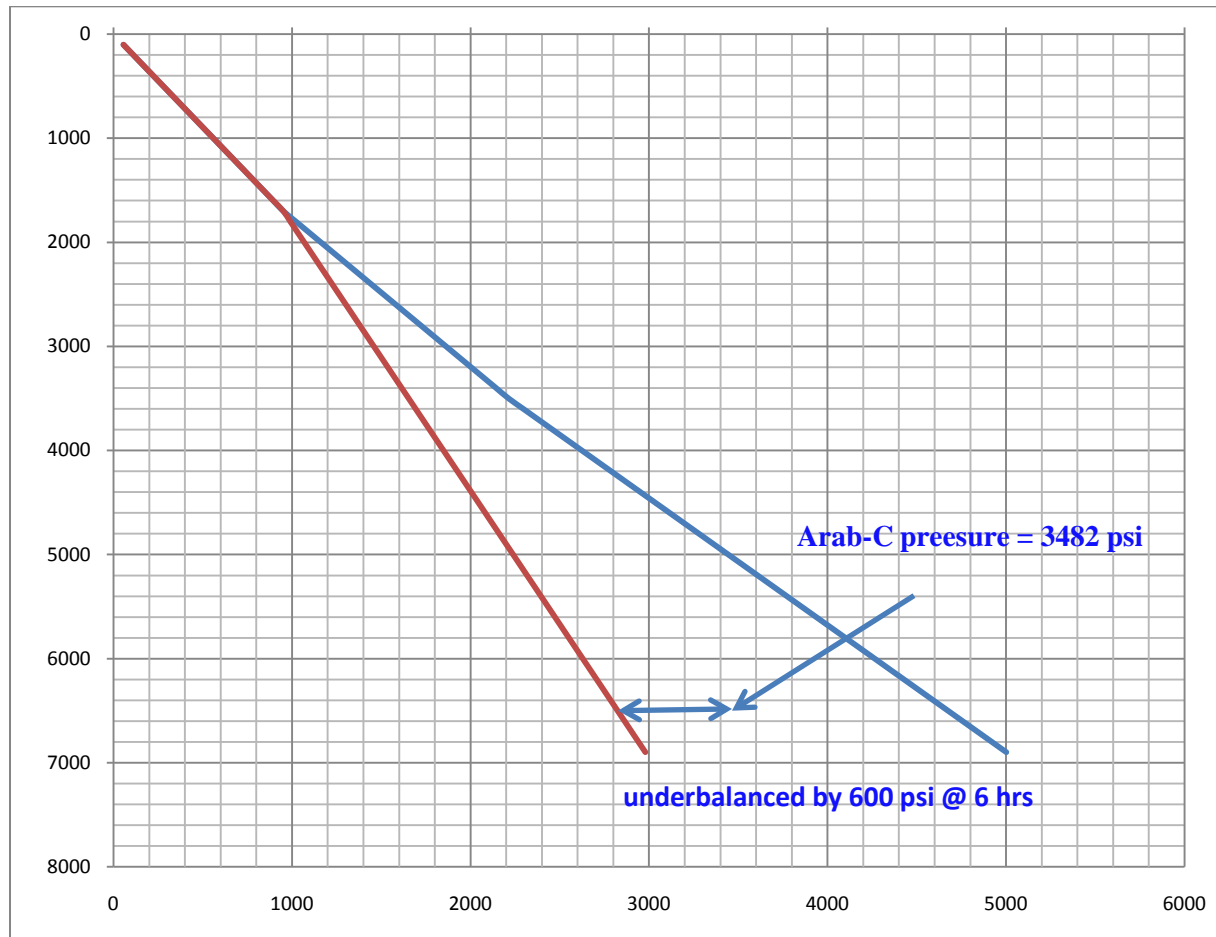
Well-C



Figure#58: Behavior of cement column pressure after 6 hrs from cement placement (well-C)

Six hours later, the cement hydrostatic pressure dropped significantly by 700 psi. In this amount of drop caused communication between formations.

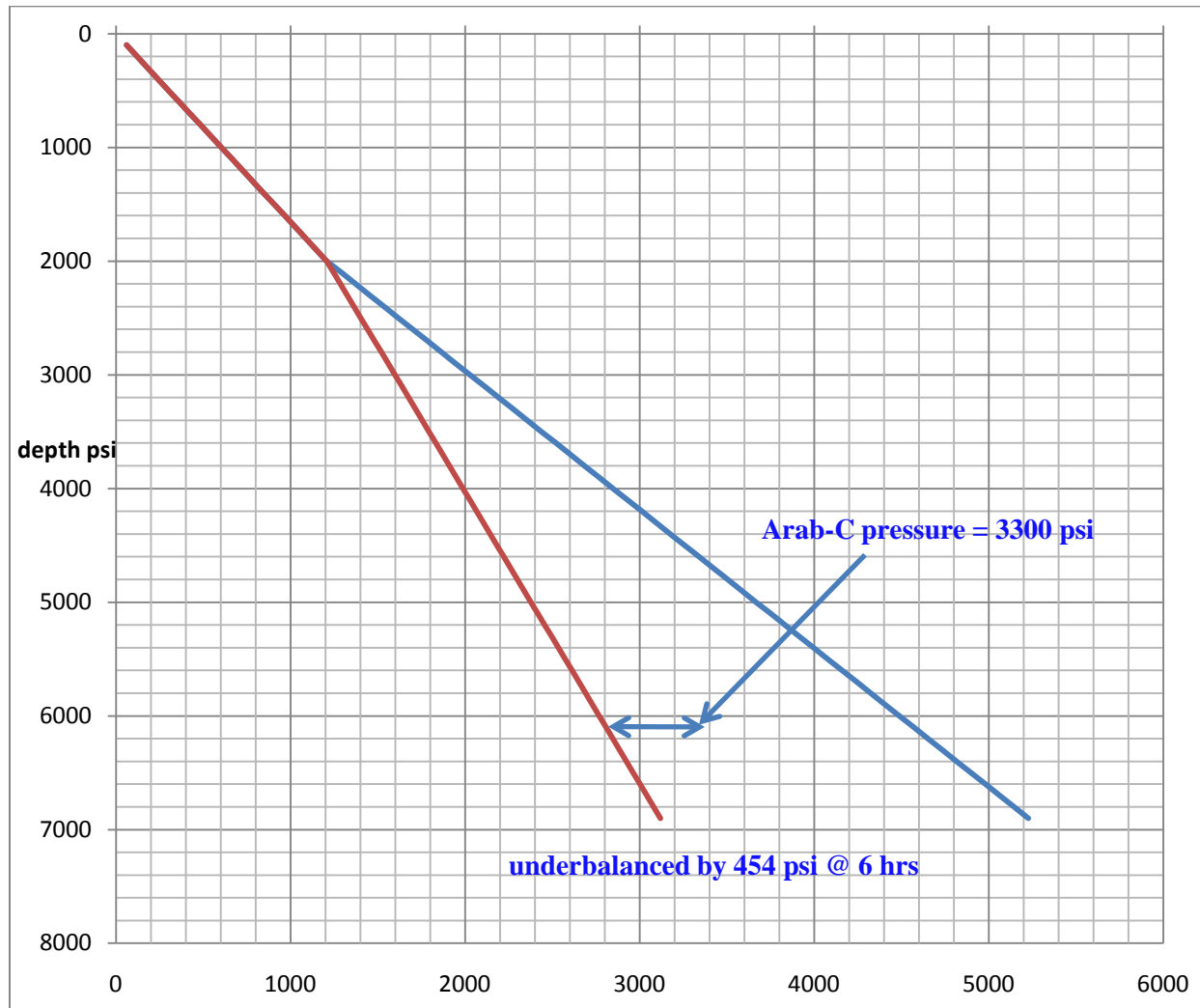
Well-D



Figure#59: Behavior of cement column pressure after 6 hrs from cement placement (well-D)

Communication between Arab-C and D formations has occurred as cement failed to develop enough compressive strength before the pressure of cement fell down below Arab-C pressure. It is clear from the graph that cement pressure had encountered a high drop in pressure of 600 psi while waiting on cement.

Well-E



Figure#60: Behavior of cement column pressure after 6 hrs from cement placement (well-E)

Six hours later, the cement hydrostatic pressure dropped significantly by 250 psi. In this amount of drop caused communication between formations.

It is an accepted fact in the industry that loss of hydrostatic pressure in the cement column occurs immediately after the cement was spotted in place due to build up of cement gel strength and reduction in cement volume as a result of hydration process and cement fluid loss to permeable formations. Arab-C has high reservoir pressure. Hence, it was easy for the cement column to be underbalanced against Arab-C reservoir before it was able to develop a static gel strength of 500 lb/100 ft² (threshold limit believed that can resist inflow of formation fluids). When the under balance occurred, inflow of water from Arab-C reservoir had contaminated the cement column in the annulus. Actual reduction in hydrostatic pressure experienced by a cement column is dependent on the development of its gel strength and reduction in the slurry volume. To illustrate the occurrence of water flow from Arab-C reservoir was experienced during the primary cementing job in Wells A and B, the pressure loss profile calculated from Cooke et al's data (i.e., at 39 psi/100' at below TOC (top of cement) after 6 hours of cement placement) is used. As shown below, the loss in the hydrostatic pressure possibly caused the cement column to be underbalanced against Arab-C.

The main factor that caused poor primary cementing result across Arab-C behind 7" liner is believed to be due to loss of hydrostatic pressure in the cement column after it was spotted in place in the annulus. The loss of hydrostatic pressure in a cement column is unavoidable since it is inherent to the cement hydration process.

5.3.2 Setting liner Top packer

All 7” liners were set with liner top packer. This has isolated the hydrostatic pressure from acting down onto the annulus and formations below. As a result, pressure on top of Arab-C decreased by 1800 to 2200 psi below Arab-C pressure right after cement placement depending on top of liner depth. This has encouraged influx from the formation into the annulus.

5.3.3 Long cement columns

Long cement column had contributed to loss of hydrostatic fluid column pressure exerting on Arab-C formation. It is a common sense that the hydrostatic pressure as well as transmissibility of cement drop during gelation time and become both zero at the end of this process. Limiting the height of cement column will aid in reducing effect of gelation and ensures that much more pressure will exert on the formation as opposed to use of long cement column.

Chapter 6

Conclusion

The objectives of this work are to investigate the root causes of poor cementing between Arab-C and D formations and suggest solutions to alleviate it. Based on the finding obtained after reviewing field practice and investigating the effect of Arab-C water on cement, the following conclusions are drawn:

- Both three month and six month tests results confirmed that Arab-C water is not detrimental to cement during this period from mechanical or chemical engineering point of view.
- The root cause of communication problem was found to be clearly the loss of hydrostatic pressure before cement attained enough compressive strength.
- Cementing practices were perfect except when setting liner top packer and use of long liner lap which encouraged water influx to attack and contaminate cement.
- Solutions including use of short cement column, elimination of liner to packer, applying annular pressure and use of zonal isolation packer between C and D formations will help avoid cement contamination due to water influx during WOC. Therefore, CBL (cement bond log) should be run immediately after cement job such that corrective measures can be taken on timely manner.

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